The Effect of Battery Ageing on Energy Storage Economy in Plug-in Hybrid Electric Vehicles is being Studied

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***Abstract*—During the utilization of PHEV, frequently discharge and charge cycles will inevitably lead to the battery aging, which affects the energy management and further affects the vehicular economy. The main purpose of this paper is to investigate the influence of battery aging on energy management economy for PHEV. Four lithium cells under different SoH are used to represent four different aging conditions during the vehicular utilization. Second-order RC model is employed as the battery model to illustrate the characteristic of battery aging. Based on a series PHEV model, two extreme matching schemes of battery topology are considered and analyzed. The influence of battery aging on vehicular economic performance is finally disclosed.**

Keywords—Plug-in hybrid electric vehicle; lithium battery; energy management; matching; economy.

I. INTRODUCTION

Different from the conventional internal combustion engine (ICE) vehicles, Plug-in hybrid electric vehicles (PHEVs) are generally equipped with an onboard high-capacity battery pack that can be recharged from power grid as one of the vehicular power sources [1]. As a result, PHEVs have lower harmful emissions and higher fuel economy than the conventional ICE vehicles [2-3]. However, with frequently charge and discharge cycles during the utilization, the onboard battery pack will inevitably performs some aging symptoms, such as power fade and capacity loss, which will affects the energy management and further affects the vehicular economy [4]. In this paper, four lithium cells under different state of health (SoH) are used to represent four different aging conditions during the vehicular utilization. Second-order RC model is employed as the battery model to illustrate the characteristic of battery aging. Based on a series PHEV model, two extreme matching schemes of battery topology are considered and analyzed. Finally, the influence of battery aging on vehicular economic performance is disclosed and investigated.

The remainder of this paper is organized as follows: the battery experiment and modeling are presented in section 2; the PHEV power system modeling is presented in section 3; the power management strategy is described in section 4; the simulation results are shown and analyzed in section 5; the conclusion is given in section 6.

II. BATTERY EXPERIMENT AND MODELING

A. Battery model

Second-order RC model is used as the battery model, in which the first RC block reflects electrochemical polarization and the second RC block describes concentration polarization, as shown in Fig. 1. The electrical behavior of this model can be expressed as:

$$\begin{cases} U_{t,k+1} = U_{oc} - I_{L,k+1}R_0 - U_{p1,k+1} - U_{p2,k+1} \\ U_{p1,k+1} = U_{p1,k}e^{\frac{-\Delta t}{\tau_1}} + I_{L,k}R_{p1}(1-e^{\frac{-\Delta t}{\tau_1}}),\ \tau_1 = R_1C_1 \\ U_{p2,k+1} = U_{p2,k}e^{\frac{-\Delta t}{\tau_2}} + I_{L,k}R_{p2}(1-e^{\frac{-\Delta t}{\tau_2}}),\ \tau_2 = R_2C_2 \end{cases} \quad (1)$$

where $U_{t,k+1}$ is the terminal voltage at (k+1)-th time step, $I_{L,k+1}$ is the battery load current at (k+1)-th time step, U_{oc} is the open circuit voltage, R_{chg} and R_{dis} are the charge and discharge resistance, respectively, R_{p1} and R_{p2} are the first and second polarization resistance, respectively, τ_1 and τ_2 are the first and second polarization resistance, respectively, C_{p1} and C_{p2} are the first and second time constant, respectively, $U_{p1,k+1}$ and $U_{p2,k+1}$ are the first and second polarization voltage at (k+1)-th time step, respectively, Δt is the time interval.

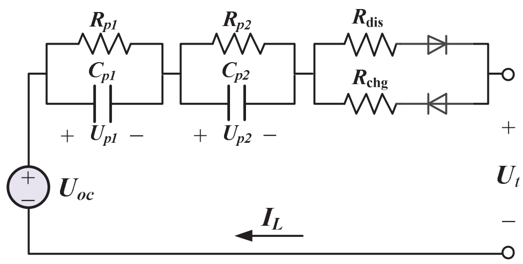

Fig. 1. Diagram of second-order RC model

B. Experiments and parameter identification

TABLE I. SOH OF THE BATTERIES

Cell No.	1	2	3	4
SoH	96.21%	90.70%	85.76%	79.34%

To illustrate characteristic of battery aging, four lithium cells are employed here to represent four varying aging status, as listed in Table 1. The nominal capacity and nominal voltage of the employed cell are 1.35 Ah and 3.2 V, respectively. Here, the capacity of the battery is employed to denote the SoH, described as:

$$SoH = \frac{C_{\text{aged}}}{C_{\max}} \times 100\% \qquad (2)$$

where C_{aged} represents the maximum charging capacity which can be measured from the aged battery, $C_{\max}$ represents the maximum charging capacity which can be measured from the new battery

To identify the parameters of the battery model, charging and discharging experiments are carried out on the four cells at urban dynamometer driving schedule (UDDS). Based on the measured battery responses, parameter of battery model can be identified by genetic algorithm (GA) [5-6]. Here, U_{oc}, R_{dis} and R_{chg} are treated as a function of SoC, while R_{p1}, R_{p2}, τ_1 and τ_2 are treated as a constant. The identification results are shown in Fig. 2. From Fig. 2 (a-c), the variation of U_{oc} is tiny during battery aging while two resistances increase remarkably. From Fig. 2 (d-e), two polarization resistances and the first time constant change slightly with cell aging but the second time constant rises markedly for the deeply aging cell. It is seen in Fig. 2 (f) that the maximum identification error is less than 42mV. Thus, this battery model can fit the characteristic of the aging cells commendably

III. PLUG-IN HYBRID ELECTRIC VEHICLE MODELING

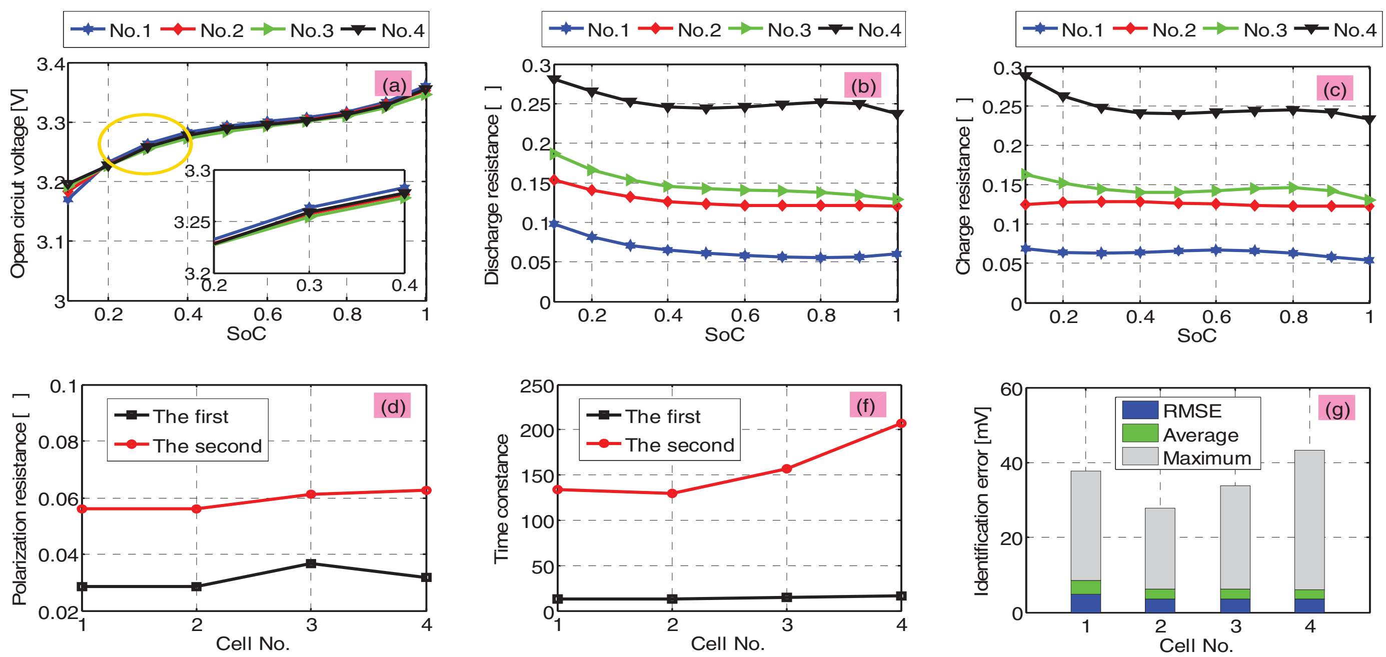

Fig. 2 Identification result of the employed cells: (a) Open circuit voltage; (b) Discharge resistance; (c) Charge resistance; (d) Polarization resistance; (f) Time constant; (g) Identification error.

A. Power system modeling

The configuration of power system in the PHEV considered in this paper is shown in Fig.3. This hybrid power system has a serious topology, in which the topological lithium battery pack is utilized as the onboard energy storage system (ESS) to provide electrical power to an electric motor, and an engine-generator set is employed as the assistance power unit (APU). The main parameters of APU and powertrain can refer to Ref. [7].

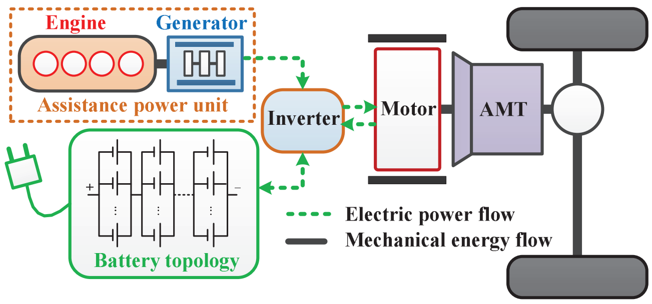

Fig. 3. Schematic of PHEV power system

B. Battery pack topology matching

As shown in Fig.3, the topology of lithium battery pack needs to be determined. Since the battery will be gradually degradation in use, aging should be taken into account when matching the topology. In order to explore the aging effect under different matching cases, two extreme matching schemes are introduced into the investigation:

(1) **Scheme #1**: matching based on Cell No.1, which only considers the new battery performance;

(2) **Scheme #2**: matching based on Cell No.4, which considers the worst performance of the aging battery.

Notice that individual cells in the battery pack are considered to be consistent to reflect the extreme cases.

The matching problem can be formulated as an optimization problem to minimize the total number of battery cells in topology with a certain driving cycle Φ, in which the power demand is only supplied by battery pack:

$$\min\ N\left(n_{\mathrm{s}}, n_{\mathrm{p}}\right)=n_{\mathrm{s}} n_{\mathrm{p}}$$

$$s.t.\begin{cases}\min\left(SoP_{\mathrm{dis}}(\Phi)\right) \geq \lambda_s \max\left(P_{\mathrm{req}}(\Phi)\right) \\ \max\left(SoP_{\mathrm{chg}}(\Phi)\right) \leq \lambda_s \min\left(P_{\mathrm{req}}(\Phi)\right) \\ U_{\text{lower}} \leq n_s U_{\text{nom}} \leq U_{\text{upper}} \\ z_{\text{lower}} \leq z(\text{end}) \leq z_{\text{upper}} \\ n_{\mathrm{s}}>0, n_{\mathrm{p}}>0,\ n_{\mathrm{s}} n_{\mathrm{p}} \in \mathbb{Z}\end{cases} \tag{3}$$

where n_s is the number of module connected in series, n_p is the number of cells connected in parallel, N is the total number of cells, P_{req} represents the power demand, λ_s is the safety design factor, U_{nom} is the cell nominal voltage, U_{lower} and U_{upper} are upper bound and lower bound of the operational voltage, respectively, z_{lower} and z_{upper} are upper bound and lower bound of expected terminal SoC, respectively, SoP_{dis} and SoP_{chg} represent the discharge and charge maximum battery power which can be estimated by the following equations [8]:

$$\begin{cases} I_{\max}^{\mathrm{dis}}=\dfrac{U_{oc}\left(z_k\right)-U_{p1,k+1}-U_{p2,k+1}-U_{t,\min}}{\dfrac{\eta_c \Delta t}{C_{\text{aged}}} \left.\dfrac{\partial U_{oc}(z)}{\partial z}\right|_{z=z_k}+R_{dis}} \\ I_{\min}^{\mathrm{chg}}=\dfrac{U_{oc}\left(z_k\right)-U_{p1,k+1}-U_{p2,k+1}-U_{t,\max}}{\dfrac{\eta_c \Delta t}{C_{\text{aged}}} \left.\dfrac{\partial U_{oc}(z)}{\partial z}\right|_{z=z_k}+R_{chg}} \\ SoP_{\mathrm{dis}}=n_s n_{\mathrm{p}}\left(I_{\max}^{\mathrm{dis}} U_{t,\min}\right) \\ SoP_{\mathrm{chg}}=n_s n_{\mathrm{p}}\left(I_{\max}^{\mathrm{chg}} U_{t,\max}\right)\end{cases} \tag{4}$$

where η_c is the columbic efficiency, $U_{t,\min}$ and $U_{t,\max}$ are upper bound and lower bound of the terminal voltage of a cell, respectively.

Here, two highway fuel economy test cycle (HWFET) (about 66 kilometers) are chosen as Φ. U_{lower} and U_{upper} are set to 200 V and 350 V, respectively. z_{lower} and z_{upper} are set to 0.18 and 0.22, respectively. λ_s is set to 1.2. This optimization problem is solved by GA.

From several trials solving this problem, we found that scheme #2 has no solution within the aforementioned constraint space. This is because the battery power capability decays more rapidly than the battery capacity during battery aging. The constraint space of scheme #1 is no longer suitable for scheme #2. Thus, zlower and zupper are relaxed to 0.22 and 0.45 for scheme #2.

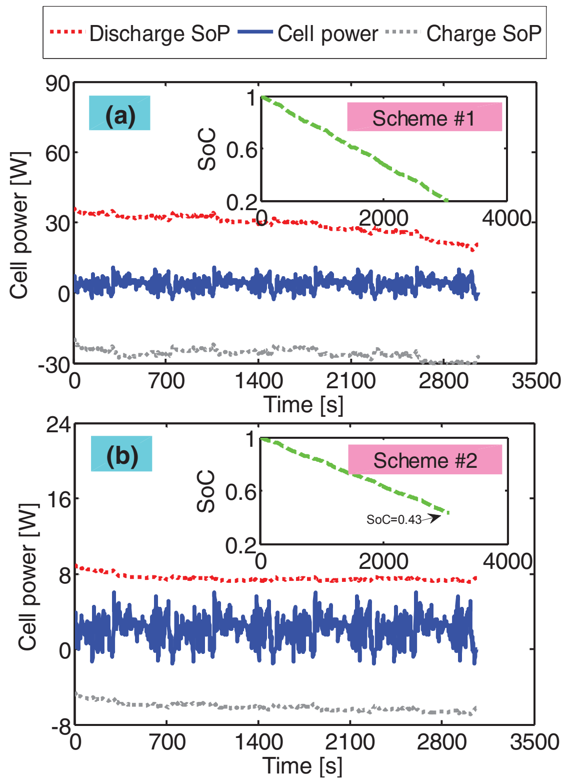

Fig. 4. Matching results: (a) scheme #1, (b) scheme #2

TABLE II. BATTERY TOPOLOGY MATCHING RESULT

Scheme	n_s	n_p	N	Rise
#1	95	35	3325	--
#2	84	70	5880	+76.8%

After calculation, the topology matching result is described in Table 2 and Fig. 4. It is seen in Fig.4 that the SoP of deeply aging cell has markedly declined, and the SoC of the deeply aging cell has markedly increased. This is because scheme #2 increases the number of cells to meet the power demand. From Table 2, the total number of battery cells in scheme #2 increases by 76.8% compared to scheme #1. The result shows that battery aging makes a great influence in battery matching economy.

IV. ENERGY MANAGEMENT STRATEGY

A. *Power control rules*

Different from the conventional HEVs, PHEVs can not only work in charge sustaining (CS) mode, but also operate in charge depleting (CD) mode.

Assuming the battery pack is full charged, PHEV operates with CD mode during the primary phase of the journey. In this mode, the power demand is supplied by battery pack. Only when battery power is insufficient, APU turns on and provides auxiliary power. Consequently, the vehicle can make full use of the renewable electric energy source.

When battery SoC reaches a relative low threshold (here, it is 0.2), another operation mode, CS mode, will be activated. In this mode, APU is the main power source while battery pack is only responsible for recovering kinetic energy during braking. A detailed mathematical description of the power management strategy is described in Table 3, in which P_B and P_E represent the battery power and engine power, respectively, η_{batt} and η_{APU} represent the battery efficiency and APU efficiency, respectively, υ_{elec} and υ_{fuel} represent the battery efficiency and APU efficiency, respectively.

TABLE III. DESCRIPTION OF THE POWER MANAGEMENT STRATEGY

SoC	Modes	Control rules
≥ 0.2	CD	$\begin{cases} P_B = \min\left\{\dfrac{P_{req}}{\eta_{Batt}}, SoP_{dis}\right\} \\ P_E = \dfrac{P_{req} - P_B\eta_{Batt}}{\eta_{APU}} \end{cases}$
< 0.2	CS	$\begin{cases} P_E = \max\left\{0, \dfrac{P_{req}}{\eta_{APU}}\right\} \\ P_B = \max\left\{(P_{req} - P_E)\eta_{Batt}, SoP_{chg}\right\} \end{cases}$

B. *Consumption cost*

Since the power source of PHEV is supplied by electricity and fuel, the consumption cost is calculated by the combination of electricity and fuel:

$$\text{cost} = \sum_k \{\upsilon_{elec} P_{Batt}(k)\Delta t\} + \sum_k \{\upsilon_{fuel} P_E(k)\Delta t\} \tag{5}$$

V. SIMULATION AND ANALYSIS

For a more comprehensive study of aging effect, two driving cycles, UDDS and extra urban driving cycle (EUDC), are employed to simulate the urban condition and suburban condition, respectively. The battery pack is assumed to be full charged. To ensure the journey can be covered with two operating modes, the driving distance is set to 130 km here.

The consumption cost of the simulation result is shown in Fig. 5. It is seen that the consumption cost of PHEV is rising during battery aging. For a certain driving cycle, the cost of scheme #2 is lower than that of scheme #1. This is because the large number of cells in scheme #2 can provide more low cost electric energy. However, the increment of battery cells will lead to a greater impact of aging. It can be seen that the cost of scheme #2 is more affected by aging.

According to section 1 and section 2, we have found that battery aging will cause capacity loss and parameter change. But the impacts of these aging symptoms on energy management economics have not been disclosed. Here, we will take Cell No.1 as a benchmark to investigate the contribution of battery aging parameters on energy management economy.

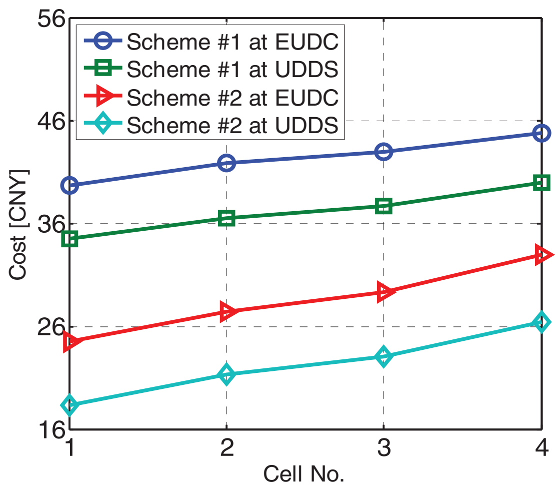

Fig. 5. Cost of simulation results

Fig. 6 shows the contribution of battery aging parameters on consumption cost, in which the percentage of cost increment is calculated based on the benchmark. According to Fig. 6 (a-d), the following conclusions can be summarized:

(1) Capacity loss and parameters change during the battery aging lead to a cost increment. The capacity loss and resistance increment are the most important factors that lead to the cost increment during aging.

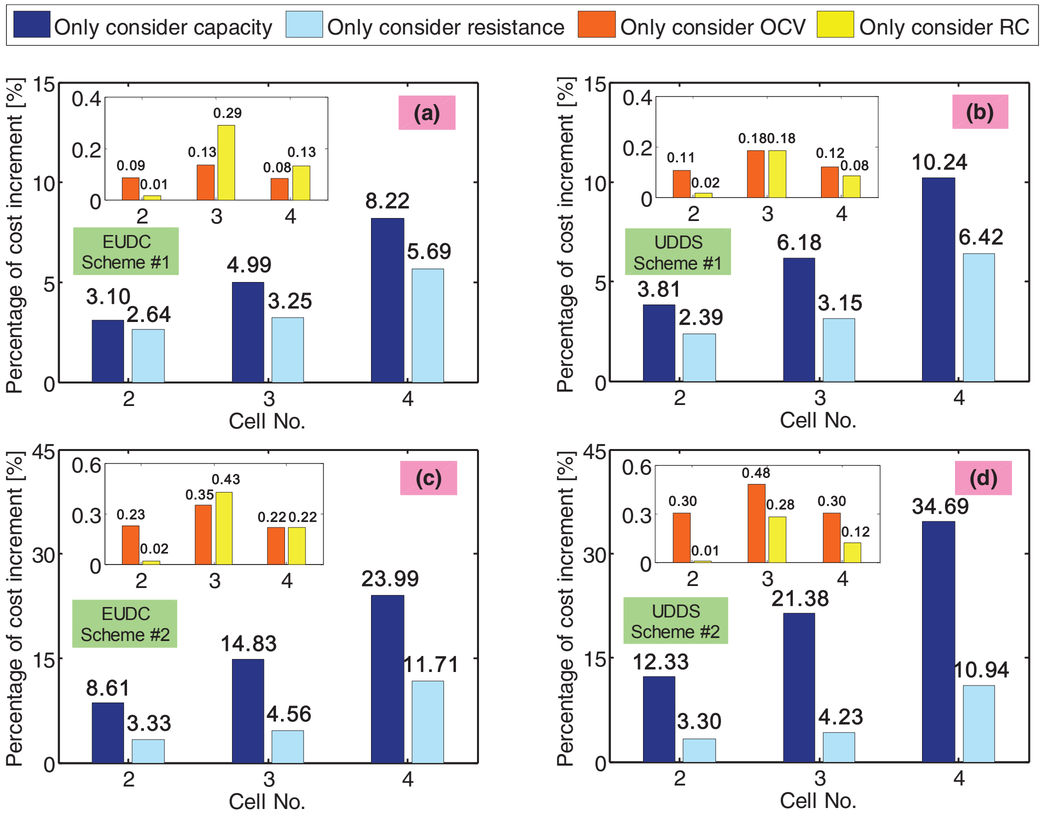

Fig. 6 Contribution of battery aging parameter to consumption cost: (a) Simulation at EUDC with scheme #1; (b) Simulation at UDDS with scheme #1; (C) Simulation at EUDC with scheme #2; (d) Simulation at UDDS with scheme #2;

(2) With scheme #2, the influence of battery aging is more pronounced. This indicated that the larger number of battery cells will lead to more pronounced aging effects.

(3) The capacity loss that caused by aging is the greatest contributor to the cost increment. The influence of capacity and resistance increases with the decrease of SoH.

(4) The influence of OCV and RC are very tiny and almost negligible. With the decreasing of SoH, these influences display firstly enhanced and then weakened.

(5) The influence of aging in UDDS is more remarkable than that in EUDC. This is because the power demand in urban condition is more inclined to the battery under the aforementioned strategy.

VI. Conclusion

In this paper, four lithium cells under different SoH are used to represent four different aging conditions during the vehicular utilization. Second-order RC model is employed as the battery model to illustrate the characteristic of battery aging. Based on a series PHEV model, two extreme matching schemes of battery topology are considered and analyzed. Finally, the influence of battery aging on vehicular economic performance is disclosed and investigated.

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