

Citation for published version:

Li, S, Gu, C, Zhao, P & Cheng, S 2021, 'Adaptive energy management for hybrid power system considering fuel economy and battery longevity', *Energy Conversion and Management*, vol. 235, 114004.
<https://doi.org/10.1016/j.enconman.2021.114004>

DOI:

[10.1016/j.enconman.2021.114004](https://doi.org/10.1016/j.enconman.2021.114004)

Publication date:

2021

Document Version

Publisher's PDF, also known as Version of record

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Adaptive energy management for hybrid power system considering fuel economy and battery longevity

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ARTICLE INFO

Keywords:

Plug-in hybrid electric vehicles
Energy management
Hierarchical optimization
Energy consumption
Total life-cycle costs

ABSTRACT

The adoption of hybrid powertrain technology brings a bright prospective to improve the economy and environmental friendliness of traditional oil-fueled automotive and solve the range anxiety problem of battery electric vehicle. However, the concern of the battery aging cost is the main reason that keeps plug-in hybrid electric vehicles (PHEV) from being popular. To improve the total economy of PHEV, this paper proposes a win-win energy management strategy (EMS) for Engine-Battery-Supercapacitor hybrid powertrains to reduce energy consumption and battery degradation cost at the same time. First of all, a novel hierarchical optimization energy management framework is developed, where the power of internal combustion engine (ICE), battery and super capacitor (SC) can be gradationally scheduled. Then, an adaptive constraint updating rule is developed to improve vehicle efficiency and mitigate battery aging costs. Additionally, a control-oriented cost analyzing model is established to evaluate the total economy of PHEV. The quantified operation cost is further designed as a feedback signal to improve the performance of the power distribution algorithm. The performance of the proposed method is verified by Hardware-in-the-loop experiment. The results indicate that the developed EMS method coordinates the operation of ICE, driving motor (DM) and energy storage system effectively with the fuel cost and battery aging cost reduced by 6.1% and 28.6% respectively compared to traditional PHEV. Overall, the introduction of SC and the hierarchical energy management strategy improve the total economy of PHEV effectively. The results from this paper justify the effectiveness and economic performance of the proposed method as compared to conventional ones, which will further encourage the promotion of PHEVs.

1. Introduction

Electrification of the automotive industry is one key step towards environmental protection [1–3]. Many countries have set both short-term and long-term strategies to encourage the adoption of PHEVs [4,5]. However, the concern of battery degradation cost is still the main barrier for PHEVs to gain popularity in customers [6,7]. To improve the economic efficiency of PHEV, a large volume of studies in recent years have investigated PHEV energy management to reduce fuel consumption and prolong the lifespan of batteries.

The configuration in Fig. 1(a) is one of the most commonly used PHEV structures, whose power system consists of two types of energy

sources: internal combustion engine and battery [8–11]. The Integrated Starter Generator (ISG) is used to generate electricity and charge the battery to improve the efficiency of ICE. With this configuration, many researchers have developed various techniques to improve the economy of PHEV in recent years [12–15]. An evolutionary algorithm based on-line energy management method was proposed in [16] to improve the fuel economy of a hybrid electric vehicle. The HIL results demonstrate that the proposed algorithm can save 10.7% of fuel consumption compared to the conventional energy management method. Further, the distributed cooperative formation control method is used in [17] to reduce fuel consumption of hybrid electric vehicles. Experiment results indicate that the reinforcement learning algorithm can save 2.04% of

Abbreviations: EVs, Electric vehicles; PHEV, Plug-in hybrid electric vehicles; EMS, Energy management strategy; ICE, Internal combustion engine; SC, Super capacitor; DM, Driving motor; ISG, Integrated Starter Generator; HESS, Hybrid energy storage system; DP, Dynamic programming; HIL, Hardware-in-the-loop; WT, Wavelet transform; RCC, Rain-flow cycle counting; SoC, State of charge; DOD, Depth of discharge; C2F, Cycles to Failure; CTUDC, Chinese typical urban driving cycle.

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<https://doi.org/10.1016/j.enconman.2021.114004>

Received 22 January 2021; Accepted 26 February 2021

Available online 16 March 2021

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energy consumption compared to the optimization-based EMS.

Nevertheless, in some operation modes or control algorithms, fuel economy is improved by overloading the battery system, which will impair battery longevity [18,19]. Thus, it is necessary to constrain battery degradation cost in the EMS of PHEV. The battery aging cost is considered in [20], and the Pontryagin's principle is used to minimize the total cost of energy consumption and battery degradation. Results indicate that battery is protected effectively, and the degradation cost is reduced significantly (10.6%). However, there is a tradeoff between energy consumption and battery degradation in traditional PHEVs. The reduction of energy consumption means the higher utilization degree of the battery, which will inevitably impair battery lifespan and increase its degradation cost. In other words, it is difficult to reduce energy consumption and battery degradation cost at the same time [21,22].

In recent years, the development of hybrid energy storage system (HESS), particularly power electronics and SC technologies, brings a promising prospect to improve the economy of PHEVs [23–26]. Power electronics based energy management converter is proposed in [27] to enable the usage of SC system in PHEVs. Four different power electronic converter topologies and control strategies are designed and compared, providing viable solutions for on-board power management of PHEVs with SC system. A Dual-source PHEV topology is studied in [28], where SCs are included to increase the dynamic response of PHEVs and prolong battery life. HIL experiment results reveal that the peak power and cycles of batteries can be reduced significantly by SCs. However, the endurance mileage of dual-source PHEVs is not satisfactory to customers, because the energy density of battery and SC is far less than fossil fuel [29].

To improve the endurance mileage and economy of PHEV, the

Triple-Source powertrain structure emerges recently [30–32]. As shown in Fig. 1(b), compared to the powertrain configuration in Fig. 1(a), an SC system is connected to the power bus of PHEV energy system by a bi-directional DC-DC converter [33–35]. The idea is to use SCs as a power buffer to protect battery from high C-rate operations. The optimal topology and economy of Triple-Source powertrain scheme are investigated in [36]. Simulation results reveal that the hybrid energy storage system, including batteries and SCs, can effectively extend battery life-span and reduce PHEV operating costs.

However, there is still a challenge regarding the efficient power distribution between three power sources according to their different characteristics. The optimal power management of Triple-Source powertrain is a complex optimization problem with three different optimization variables and two optimization objectives. To the authors' best knowledge, only limited research has been dedicated to this issue. An energy management method based on Dynamic programming (DP) algorithm is proposed in [37] to optimally allocate energy between engine-generator, battery and SC. Experiment results show that the proposed control strategy improves 11.28% of fuel economy compared to traditional PHEVs. However, battery degradation cost is not considered. In addition, the working points of the engine, motor and HESS cannot be fully optimized due to the intrinsic optimization ability of DP algorithm, constraining PHEV economy.

To address above research gaps and better utilize the Triple-Source energy storage system in PHEV, this paper proposes a novel win-win energy management strategy to simultaneously improve the fuel economy and prolong the battery life. In this hierarchical optimization-based framework, the power of ICE, battery and SC system can be scheduled gradationally based on their different characteristics. In the first stage, a

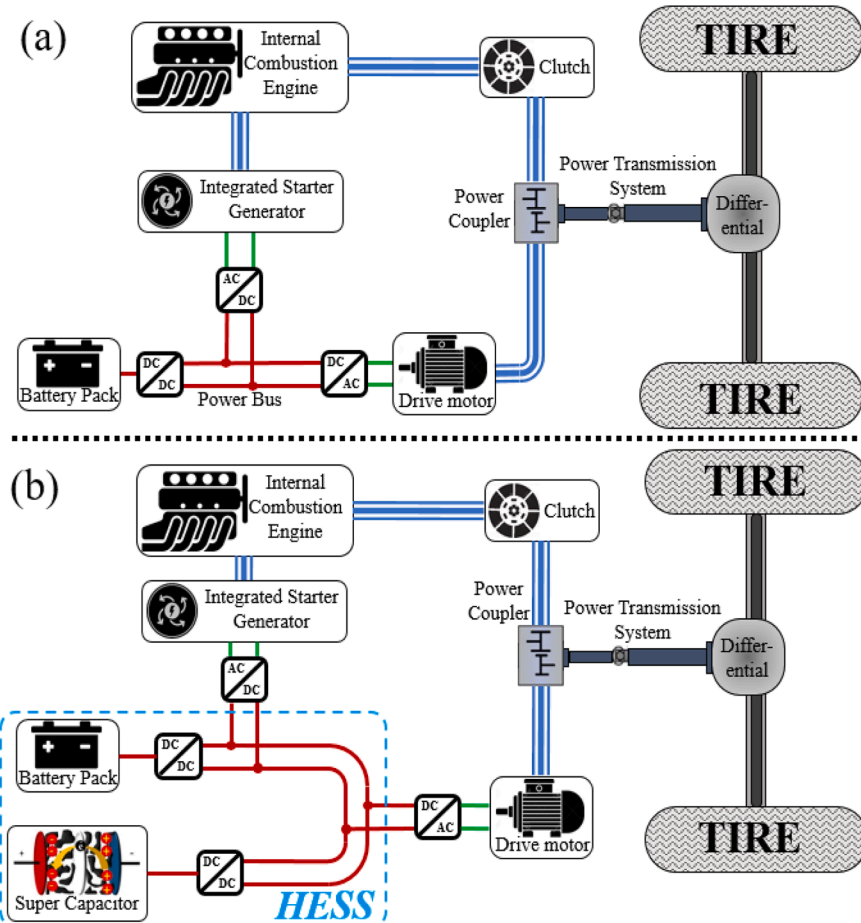


Fig. 1. Comparison of energy storage system structure in traditional PHEV (a) and Triple-Source powertrain structure (b).

novel adaptive constraint update DP algorithm is proposed to improve the efficiency of the ICE, DM and HESS in PHEV. In the second stage, a control-oriented cost analyzing model is developed, which can comprehensively evaluate the fuel economy and battery degradation cost with PHEV operation. The quantified integrated cost is designed as a feedback signal to improve the performance of the PHEV energy management strategy. The dynamic performance of the proposed energy management strategy is validated through Hardware-in-the-loop (HIL) experiment, and the economy of PHEV, including the fuel, electricity and battery degradation cost in total life cycle, are verified by numerical analysis.

The key contributions of this paper are as follows:

- 1) Comparing to the most existing literature about ICE-battery PHEV energy management, this paper mainly focuses on the ICE-battery-SC triple-source powertrain. A novel hierarchical optimization energy management framework is proposed, in which the operation of Triple-Source powertrain can be scheduled gradationally, thus the computational complexity of energy management issue can be reduced significantly.
- 2) Comparing to the Triple-Source powertrain EMS studied in previous literature, which mainly focuses on improving the fuel economy but neglects the battery aging cost, this paper is the first attempt to investigate and mitigate battery aging phenomenon in Triple-Source powertrain control issue. With the proposed EMS, the fuel cost and battery aging cost can be reduced at the same time, and thus the total economy of PHEV can be significantly improved.
- 3) Comparing to the conventional DP algorithm-based EMS, this paper studies a novel adaptive constraint updating method to adjust the working area of vehicle dynamical system. It designs a novel control-oriented PHEV cost analyzing model, where the fuel economy and battery degradation phenomenon can be evaluated comprehensively with the operation of PHEV. The quantified operation cost is used as a feedback signal to improve the performance of the energy management system.

Furthermore, the theoretical and practical significance of the developed methodology can be summarized as follows:

- 1) The designed hierarchical optimization energy management framework and the corresponding adaptive power distribution method can further perfect the design and management theory of PHEV with Triple-Source powertrain.

- 2) The simulation and experiment results in this study indicate that the use of SC energy storage can further improve the total economy of PHEV, which provides a new power system solution for the automobile industry and will further improve the promotion of the transportation electrification process.

The rest of the paper is organized as follows: The proposed hierarchical optimization-based energy management framework is in Section II.A. Section II. B ~ D presents the details and the mathematical principles of the proposed method. The performance of the proposed method is analyzed in Sections III, followed by concluding remarks in Section IV.

2. Hierarchical energy management framework

Hierarchical model has been widely used in industry and hierarchical optimization is of great significance to complex system control [38,39]. To reduce the computational complexity of Triple-Source powertrain energy management and improve the economy of PHEV, a new energy management based on hierarchical optimization is developed in this section, where ICE, battery and SC system are scheduled gradationally. The structure and information flow of the proposed hierarchical optimization framework is shown in Fig. 2, which can be divided into three levels:

- 1) At the first level, the power requirement of PHEV is first divided into two parts: mechanical part (ICE) and electrical part (DM). The efficiency maps of ICE, ISG and DM, and the adaptive DP algorithm are used to obtain the optimal power sharing between ICE and DM.
- 2) At the second level, the power requirement of DM is distributed between the battery and SC systems. Wavelet transform (WT) is used to decompose the power requirement signal of DM into high-frequency and low-frequency components. To protect the battery, the high-frequency power requirement components are filtered and provided by the SC system. The low-frequency power requirements are satisfied by the battery system.
- 3) At the third level, to further improve the economy of PHEV, an adaptive strategy update signal is constructed to optimize the working condition and efficiency of ICE, DM, and energy storage system. As shown in Fig. 2, the energy consumption and battery life-cycle costs are quantified with the cost analysis model and Rain-flow cycle counting (RCC) algorithm. Furthermore, the quantified integrated cost of PHEV is designed as an adaptive feedback signal for the DP algorithm-based energy management model.

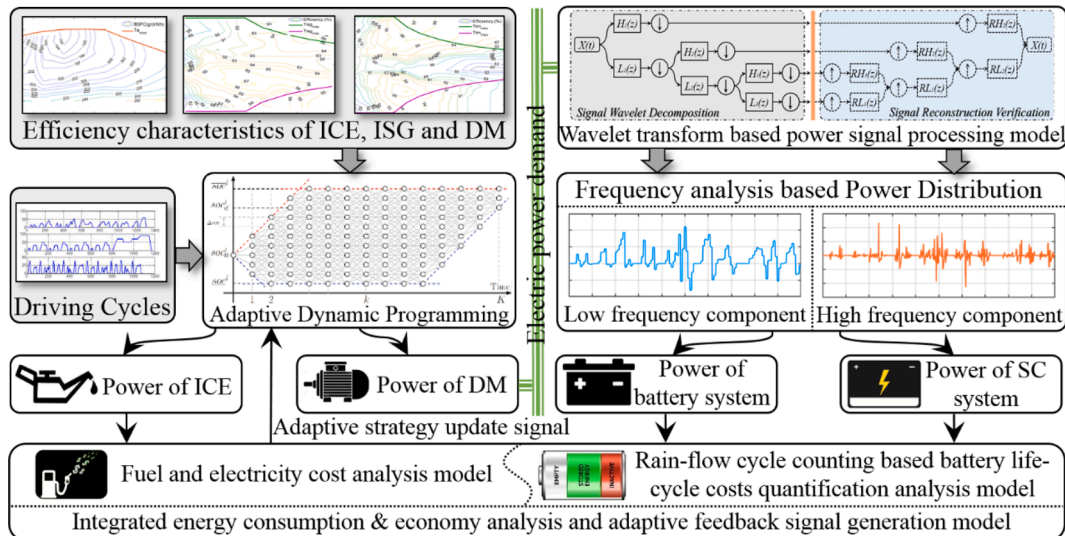


Fig. 2. Hierarchical optimization framework-based energy management strategy for Triple-Source powertrain scheme.

3. Adaptive energy management strategy for triple-source powertrain scheme

This section describes the detailed mathematical principle of the proposed hierarchical energy management strategy. First, an adaptive energy management method is developed to distribute the power requirement of the vehicle to different energy storage sectors. Then, an integrated cost analysis and adaptive feedback signal generation model is designed to quantitatively evaluate the fuel economy and battery degradation cost of PHEV.

3.1. Adaptive dynamic programming algorithm-based ICE-DM energy distribution strategy

The DP algorithm, mainly used to solve multi-stage decision-making problems [40], is employed to distribute the power between ICE and DM. The Berman optimization principle is utilized along with DP algorithm. The whole optimization is decomposed into a series of single-step optimization sub-problems, and the minimum cost function is obtained by the backward solution method [41]. Based DP algorithm, an adaptive power distribution algorithm is developed in this part, in which an energy consumption and battery life-cycle cost feedback signal is used to adjust the working area of the ICE and DM and thus further optimize the efficiency of PHEV.

The power system of PHEV is simplified as a nonlinear time-discrete system, where the battery state of charge (SoC) is selected as the system observed variable:

$$\begin{cases} \text{SoC}(t+1) = f(\text{SoC}(t), \text{Ctl}(t)) \\ \text{SoC}(0) = x_0 \end{cases} \quad (1)$$

where: $\text{SoC}(t)$ and $\text{SoC}(t+1)$ are the state of the battery at time t and $t+1$. $\text{Ctl}(t)$ is the control signal from vehicle control system, representing driver's behaviors and road conditions, including required ICE torque T_e and speed n_e , ISG torque T_{ISG} , torque T_m and speed n_m requirements of DM, state of clutch S_{clu} and braking T_{brake} from the driver. f is the system state transfer function.

To reduce the energy consumption of PHEV, the costs of fuel and electricity are constrained by the objective function (2) of the DP algorithm:

$$J = \sum_{k=0}^{N-1} F_c[\text{SoC}_k, \text{Ctl}_k] + E_c[\text{SoC}_k, \text{Ctl}_k] \quad (2)$$

where: F_c and E_c are fuel and electricity consumption costs.

Furthermore, a correction factor based adaptive constraint update method is applied in the DP to suppress battery degradation and improve energy utilization efficiency. Firstly, 3 adaptive factors: SoC attenuation APA_{soc} , engine gain factor APG_{ice} and motor gain factor APM_{dm} are defined to regulate the utilization degrees of the battery, ICE and DM respectively. The value and update rules of the 3 adaptive factors are described in Section II.C.

Then, the state of battery is constrained by (3) to avoid over-discharge:

$$\text{APA}_{\text{soc}} \cdot \text{SOC}_{\min} \leq \text{SOC}_k \leq \text{SOC}_{\max} \quad (3)$$

In optimization, the attenuation factor APA_{soc} is used to adaptively adjust the rating of exertion of the battery, the greater the APA_{soc} , the shallow the allowable depth of discharge and the shrinking battery potential utilization degree is allowed, vice versa. By adjusting APA_{soc} , the utilization degree of the battery is modulated dynamically.

The speed and torque of ICE are constrained through (4) and (5):

$$n_{e_{\min}} \leq n_{e_k} \leq n_{e_{\max}} \quad (4)$$

$$\text{APG}_{\text{ice}} \cdot T_{e_{\min}}(n_{e_k}) \leq T_{e_k} \leq \text{APG}_{\text{ice}} \cdot T_{e_{\max}}(n_{e_k}) \quad (5)$$

The ISG motor in PHEV are passive devices with defined working areas:

$$n_{\text{ISG}_{\min}} \leq n_{\text{ISG}} \leq n_{\text{ISG}_{\max}} \quad (6)$$

$$T_{\text{ISG}_{\min}}(n_{\text{ISG}_k}, \text{SOC}_k) \leq T_{\text{ISG}_k} \leq T_{\text{ISG}_{\max}}(n_{\text{ISG}_k}, \text{SOC}_k) \quad (7)$$

Eq. (6) limits the speed range of the ISG motor, and (7) describes the maximum and minimum of torque of the motor.

The DM is the main drive device in PHEV and its working mode impacts the efficiency of PHEV directly. Thus, the working area of DM is also set as a flexible one through the adaptive factor method:

$$n_{m_{\min}} \leq n_{m_k} \leq n_{m_{\max}} \quad (8)$$

$$\text{APM}_{\text{dm}} \cdot T_{m_{\min}}(n_{m_k}, \text{SOC}_k) \leq T_{m_k} \leq \text{APM}_{\text{dm}} \cdot T_{m_{\max}}(n_{m_k}, \text{SOC}_k)$$

Formula (8) describe the motor output speed range, and (9) reflects the flexible torque range of the DM. Similar to APA_{soc} , APG_{ice} and APM_{dm} are used to adaptively adjust the potential utilization of the ICE and DM in DP algorithm adaptively.

The state of the power system is defined by the Eqs. (3)–(9), and the potential utilization of DM, ICE is adjusted by the proposed adaptive constraint update method. Finally, the power transmission relationship of PHEV is defined by the following equations:

$$T_{d_k} = T_{e_k} + T_{\text{ISG}_k} + T_{m_k} + T_{b_k} \quad (10)$$

$$\begin{cases} n_{m_k} = n_{e_k} = n_{\text{ISG}_k} \text{ clutch} = 1 \\ n_{e_k} = n_{\text{ISG}_k} \text{ clutch} = 0 \\ T_{e_k} + T_{\text{ISG}_k} = 0 \text{ clutch} = 0 \end{cases} \quad (11)$$

Different from solving process in DP algorithm, in the derived energy management strategy, the working points of ICE and DM need to satisfy the actual working area:

$$T_{e_{\min}}(n_{e_k}) \leq T_{e_k} \leq T_{e_{\max}}(n_{e_k}) \quad (12)$$

$$T_{m_{\min}}(n_{m_k}, \text{SOC}_k) \leq T_{m_k} \leq T_{m_{\max}}(n_{m_k}, \text{SOC}_k) \quad (13)$$

When the derived working points in DP algorithm out of the actual working area, the corresponding ICE and DM output torque is modified to be the corresponding maximum and minimum value.

3.2. Wavelet transform-based HESS management

In the power requirement of PHEV, the high-frequency components would result in meaningless and accelerated battery degradation. According to [42], in hybrid energy storage system, the frequent delivery of transient peak power requirements can harm the battery longevity and decrease the power system efficiency. In particular, batteries are susceptible to high-frequency components in power demand which damages their chemical structure and greatly shortens their lifetime. Nevertheless, SC can absorb the transient peak power requirement in a short time without reducing their lifetime. Therefore, the second level of power distribution is achieved by using the WT algorithm, which is a well-recognized signal processing method to decompose an original signal into several components with different frequencies [43]. The discrete WT decomposes the discretized signal into several components with different resolutions based on the transfer function, and in HESS power decomposition issue, the decomposition process can be described by (14) and (15):

$$W(\tau, s) = \int_{-\infty}^{+\infty} P_{\text{dm}}(t) \frac{1}{\sqrt{s}} \varphi\left(\frac{t-\tau}{s}\right) dt \quad (14)$$

$$P_{h,l}(t) = \sum_{j \in Z} \sum_{k \in Z} W(\tau, s) \varphi_{j,k}(t) \quad (15)$$

where: s represents the degree of discretization. $\tau = k2^j, k \in Z^2$, $P_{\text{dm}}(t)$ is the power requirement of DM. $P_{h,l}(t)$ is the decomposed power profile.

As one of the most simple and fast wavelet algorithms, Haar wavelet has the shortest filter length compared with other wavelets and its wavelet transform is equal to its inverse transform. The technical disadvantage of the Haar wavelet is that it is not continuous, and therefore not differentiable. However, accounting to [44], this property can be an advantage for the analysis of signals with discrete signals. The optimal energy management of EVs can be regarded as a discrete optimal control problem, therefore, the Haar wavelet is used in our work to distribute the power between the battery and SC. The Haar wavelet function can be denoted as:

$$\varphi(t) = \begin{cases} 1, & t \in [0, 0.5) \\ -1, & t \in [0.5, 1) \\ 0, & \text{others} \end{cases} \quad (16)$$

In [45], the 3-decomposition-level wavelet-based energy management strategy has been proved to be the optimal selection for the battery-SC hybrid power system. In a comprehensive comparison of the terminal SoC, current and energy losses, it is found that 3 decomposition levels has better performances than the other decomposition levels. Therefore, the three-level Haar wavelet is used in our work to process power demand signals into high and low-frequency power (P_l, P_h). The structure of the three-level Haar wavelet transform is shown in Fig. 3.

The extracted high-frequency and low-frequency signal is expressed as equation (17):

$$\begin{cases} P_h(t) = \mathcal{I} \mathcal{C} \mathcal{W} \mathcal{T} [H_1(z) + H_2(z) + H_3(z)] \\ P_l(t) = \mathcal{I} \mathcal{C} \mathcal{W} \mathcal{T} [L_3(z)] \end{cases} \quad (17)$$

where $\mathcal{I} \mathcal{C} \mathcal{W} \mathcal{T}$ represents inverse wavelet transform.

To ensure the dynamic performance of PHEV and protect battery longevity at the same time, the high-frequency component $P_h(t)$ will be handled by the SC system and the low-frequency component $P_l(t)$ will be provided by the battery.

3.3. Integrated cost analysis and adaptive feedback signal generation model

To design a win-win energy management method between fuel economy and battery longevity, an integrated cost analysis and adaptive feedback signal generation model is established in this part. The fuel cost, electricity consumption and battery degradation of the PHEV are chosen to construct the cost feedback function in this study.

In PHEV, because of the complex road condition and braking energy recovery mechanism, the energy storage system is required to charge and discharge rapidly, frequently and sometimes deeply. The battery may be destroyed rapidly without effective protection. The degradation phenomenon of the battery is mainly affected by the number of cycles and depth of discharge (DOD). The RCC algorithm has been widely used, such as in metal fatigue estimation and energy management in micro-grid. The RCC algorithm applied in HESS has been studied in our previous work, the definition of the inputs and outputs and the detailed algorithm parameters is shown in [46].

To quantify battery degradation in PHEV, the results of the RCC method (extracted battery number of cycles and depth of discharge) are converted to full life cycle economy by the following step:

- 1) Calculate the equivalent degradation cycles (EC) of the corresponding irregular cycles based on battery Cycles to Failure (C2F) relationship (18):

$$EC(k) = MAP_{cf}(DOD(k), Crate(k)) \quad (18)$$

The manufacturer will give an experiment profile to describe the degradation character of battery, where the relationship between maximum life cycles, DOD and Crate of the battery can be derived. The C2F profile of the battery used in our work is shown in Fig. 4.

- 2) Define the equivalent battery aging factor η , which reflects the relationship between battery cycles to degradation degrees and can be defined as:

$$\eta(k) = 1/EC(k) \quad (19)$$

According to the number of cycles and DOD data obtained by the RCC algorithm, the total battery aging (TBA) and corresponding battery degradation cost are calculated as (20) and (21):

$$TBA = \sum_{k=1}^{k=n} \eta(k) \quad (20)$$

$$C_{B_aging} = PR_B \cdot TBA \quad (21)$$

When TBA is close to 1, the battery should be marked as out of service and replaced. PR_B is the price of the battery and C_{B_aging} is the degradation cost.

- 3) The operation cost of PHEV mainly includes fuel consumption costs and electricity consumption costs, which can be depicted as equation (22):

$$C_{ope} = V_{fuel} \times \rho_{fuel} + E_B \times \rho_{elec} \quad (22)$$

where: V_{fuel} and E_B are the ICE fuel consumption and DM electricity

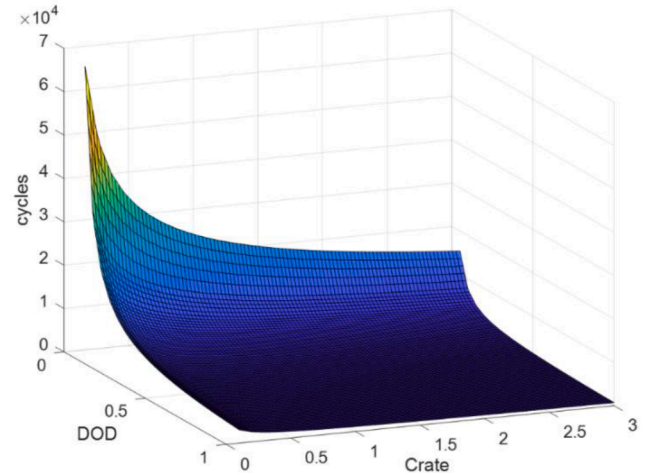


Fig. 4. The mapping relationship between DOD, Crate and equivalent cycles.

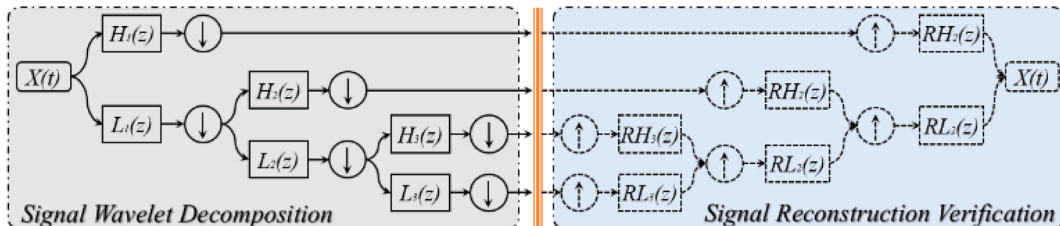


Fig. 3. The flowchart of the three-level Haar wavelet transform process.

consumption; ρ_{fuel} and ρ_{elec} are the unit prices of diesel and electricity.

To reduce the energy consumption and suppress battery degradation simultaneously, the C_{B_aging} and C_{ope} should be constrained at the same time. This is nearly impossible to be realized in traditional PHEV (battery and ICE), because the decrease of C_{ope} means the higher utilization degree of battery and the C_{B_aging} would increase inevitably. However, in the Triple-Source powertrain scheme, the SC system can help the battery and ICE work better at the same time. Therefore, in the proposed PHEV control algorithm, three adaptive factors: APA_{soc} , APG_{ice} , APM_{dm} are set to reduce energy consumption and battery degradation.

Firstly, the initial and boundaries of the adaptive factors is defined as follows:

$$\begin{cases} APA_{soc}(0) = APG_{ice}(0) = APM_{dm}(0) = 1 \\ 1 < APA_{soc}(t) < 2 \\ 0.5 < APG_{ice}(t) < 1.5 \\ 0.5 < APM_{dm}(t) < 2 \end{cases} \quad (23)$$

The initial values of adaptive factors are set as 1 to guarantee that PHEV works stably at the beginning. The value of adaptive factors indicates the available utilization potential of PHEV system. $APA_{soc}(t)$ represents the utilization potential of the battery, which is expected to be reduced by using the SC system in this paper. The upper value of $APA_{soc}(t)$ is set as 2, which constrains the battery potential utilization degree in the DP algorithm. The power requirements of DM are provided by the SC system, and the ability of the DM system to cope with overloading is very high, so the $APM_{dm}(t)$ is set with a wide boundary. To reduce fuel consumption, the usage of ICE should be reduced, so the value of $APG_{ice}(t)$ is constrained within 0.5 to 1.5.

With the operation of PHEV, adaptive factors are updated regularly to reduce energy consumption and suppress battery degradation. The update rules of APA_{soc} , APG_{ice} and APM_{dm} are given in (24) ~ (26):

$$APA_{soc}(k+1) = APA_{soc}(k) \times \begin{cases} G_{battery}^+ \nabla(\Delta C_{B_aging}) > 0 \\ G_{battery}^- \nabla(\Delta C_{B_aging}) < 0 \& \nabla(\Delta C_{ope}) > 0 \end{cases} \quad (24)$$

$$APG_{ice}(k+1) = APG_{ice}(k) \times \begin{cases} G_{ice}^+ \nabla(\Delta C_{B_aging}) > 0 \\ G_{ice}^- \nabla(\Delta C_{ope}) > 0 \end{cases} \quad (25)$$

$$APM_{dm}(k+1) = APM_{dm}(k) \times \begin{cases} G_{dm}^+ \nabla(\Delta C_{ope}) > 0 \& \nabla(\Delta C_{B_aging}) < 0 \\ G_{dm}^- \nabla(\Delta C_{B_aging}) > 0 \end{cases} \quad (26)$$

Firstly, if the battery degradation is accelerated, APA_{soc} is increased to suppress the usage of the battery; while if the increase rate of energy consumption tends to accelerate, APA_{soc} will be decreased to save fuel and improve the utilization of HESS system. Then, similar to APA_{soc} , APG_{ice} and APM_{dm} are also determined by the trend of energy consumption cost C_{ope} and battery aging cost C_{B_aging} . In the equation (24) ~ (26), $G_{battery}$, G_{ice} and G_{dm} represent the correction factor of the battery, ICE and DM respectively.

4. Hardware in the loop experiment

4.1. Experimental data set description

The Chinese typical urban driving cycle (CTUDC) is used to simulate the working scenarios of PHEV and verify the proposed methodologies. The profiles of CTUDC are shown in Fig. 5, with a driving distance of 5.897 km and driving duration of 1314 s.

In our work, the proposed methodologies will be verified through experiments and simulations on an electric bus. The configuration of the platform is the same as Fig. 1(a) and the detailed parameters are shown in Table 1.

4.2. Algorithm hardware implementation

The use of the DP algorithm reduces energy consumption and improves the economy of PHEV effectively, but the optimization process of the DP algorithm is very complicated and time-consuming, which limits the real-time and hardware application of the DP algorithm. The optimal ICE, DM and HESS working mode calculated by DP algorithm can be as a benchmark or reference for further analysis. To realize real-time control of PHEV, it is necessary to construct an online and effective controller based on the results of the DP algorithm. Nowadays, the most popular methods to realize the DP based energy management strategies in hardware is divided into two types: rule base method and neural network method. Compared to the rule base, the neural network is able to learn the energy management rules using results from DP automatically and more sufficiently, and thus it is used in this study. The constructing and training method of the neural network method has been

Table 1
Specific parameters of the experimental PHEV.

Name	Parameters	Value	Parameters	Value
ICE	Maximum power/kW	147	Maximum torque/N	804
	Idle speed/rpm	650	Maximum speed/rpm	2750
ISG	Maximum power/kW	65	Maximum torque/N	600
	Maximum speed/rpm	2800		
DM	Maximum power/kW	168	Maximum torque/N	2000
	Maximum speed/rpm	2500		
Battery	Capacity/Ah	60	Voltage/V	576
	Capacity/F	13.75	Voltage/V	576
Supercapacitor	Vehicle loaded mass/kg	18,000	Windward area/m ²	6.6
	Air resistance coefficient	0.55	Tire rolling radius/mm	473
	Rolling resistance coefficient	0.0095	Transmission efficiency	0.93

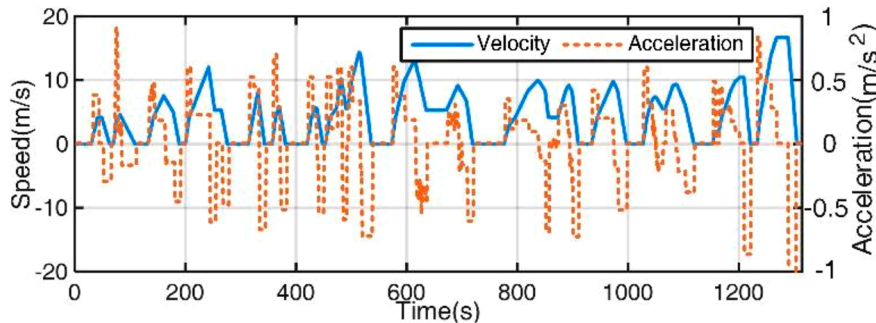


Fig. 5. The velocity and acceleration profile of the CTUDC.

well studied in Zheng Chen's work [12], the main processes are summarized in Fig. 6.

When using the WT algorithm, the power requirement of the driving motor is regarded as the input signal and the corresponding high-frequency and low-frequency output signal is used as the control signal of the SC and battery pack respectively. In this study, to better illustrate the performance of the proposed method, the CTUDC is used to simulate the working scenarios of PHEV and verify the proposed methodologies. The power demand of the vehicle is already known due to the predefined drive cycle. Therefore, the power requirement of the driving motor can be regarded as a foreknown signal which can be dealt with WT algorithm.

4.3. HIL experiment results of hierarchical optimization-based energy management strategy

The HIL experiment platform established in the previous work [47] conducted by our group is used in this study to validate the performance of the proposed PHEV energy management method. The platform mainly consists of 2 parts: control system development platform, which is used to implement the energy management strategy; real-time model system development platform, which is used to build the PHEV dynamic simulation model. In this study, all the system models and control algorithms are programmed with MATLAB/Simulink and then automatically generated to C language by the rapid code generation function.

In the proposed hierarchical energy management framework, the power requirement of the vehicle will be distributed to ICE and DM firstly. Then, the power of DM will be further distributed between the battery and SC system. The DP algorithm and WT algorithm are used to distribute the power requirement of PHEV. The power distribution result between ICE and battery are shown in Fig. 7. Subfigure (a) and (b) show the power of ICE and the DM in 1 CTUDC cycle. In conventional PHEV, the power of DM is only provided by the battery, and the battery SoC profile in 6 CTUDC cycles is shown in subfigure (c). There are many shallow charging and discharging cycles in battery SoC profile for the reason that the energy from the regenerative braking system is absorbed by the battery only, and these shallow cycles will do harm to the longevity of the battery inevitably.

The HESS (SC system) and the WT algorithm is used to mitigate the working pressure on the battery. In theory, the power distribution algorithm (the power output of ICE and DM) can always meet the power requirement of PHEV. Nevertheless, there is a difference between the DM actual output power profile and the original power requirement profile. The reason is that there is a calculation delay in HIL simulation platform, and the mechanical and electrical characteristics of the actual motor (DM in HIL) and energy storage system (battery and SC) are different for the ideal one. As shown in Fig. 8 (a), in this study, the mean power supply-demand gap can be limited to 0.35kw (2.6%). The power difference only occurs when the power requirement fluctuates drastically, according to [48], this simulation error is within the allowable range of error, it has little effect on the overall control effect. Subfigure (b) shows the low-frequency component extracted by the WT algorithm, comparing to the original power requirement profile in subfigure (a). The random and violent fluctuations have been suppressed, which

indicates that some meaningless battery charge and discharge cycles can be avoided, and thus the battery life span is prolonged. Subfigure (c) is the corresponding high-frequency component of the original power requirements which fluctuates violently and will be provided by the SC system.

The global battery SoC profile in a whole discharging cycle (6 CTUDC cycle) is shown in Fig. 9. Compared to conventional PHEV, the high-frequency power requirements are absorbed by the SC system in the proposed EMS. Thus, the shallow charging and discharging cycles of the battery are reduced effectively, indicating that the battery is protected successfully. The final SoC value in this study (16.5%) is lower than that of conventional PHEV (20%). It is because that the DM is used more frequently to reduce the working time of ICE and improve the fuel economy in the proposed strategy.

Satisfying the power requirement of the engine is of great significance to the dynamic performance of PHEV. In this study, the dynamic power supply-demand relationship of the proposed EMS is evaluated by the velocity following performance in HIL experiment. As shown in Fig. 10, in the HIL experiment, with the proposed power distribution algorithm, the actual vehicle velocity can follow the reference velocity profile dynamically, which indicated that the developed energy management strategy can distribute the power requirement of PHEV to ICE and DM effectively, and the energy storage system can provide enough power for PHEV to follow the CTUDC cycle accurately and in real-time.

The battery degradation suppression effectiveness of the proposed method is illustrated in Fig. 11. In traditional DP based EMS, the battery needs to meet all the power requirements of the DM. Thus, the battery number of cycles is as high as 432, which indicates that the battery is charged and discharged frequently and will age rapidly. Compared with traditional DP algorithm method, the SC system in DP & WT algorithm-based EMS mitigates the work pressure of the battery, and the battery number of cycles is decreased significantly (31.4%, 136 cycles). The proposed adaptive DP algorithm and feedback signal improve the utilization degree of the SC system sufficiently. As shown in Fig. 9, the number of cycles of the battery is further decreased to 246, which indicates that the battery is protected effectively by the SC system and the proposed EMS. Furthermore, it is a remarkable fact that the battery cycles under low SoC level (10%–40%) is reduced significantly (62% compared to the traditional DP method) with the proposed EMS. The cycles under low SoC level impact the battery life greatly, the reduction of cycles under low SoC level indicated that the battery life is protected successfully with the proposed EMS.

To quantitatively analyze and evaluate the performance of the proposed method, the cost of different PHEV configurations and algorithms are compared in Table 2. According to the statistical information, the longevity of PHEV is 12 years with 12 CTUDCs per day and 300 days per year. The standard price of the fuel, electricity, battery and SC is stated in literature [49]. The costs of different algorithms are calculated based on the above assumption. Compared with conventional PHEV, the Triple-Source powertrain scheme reduces the battery degradation cost significantly (22.9%), because the SC system cooperates with the battery, thus mitigating the working pressure of the battery system. However, considering the inherent constraint on the DP algorithm's optimization capability, the operation of the power system in Triple-Source powertrain scheme cannot be controlled and optimized

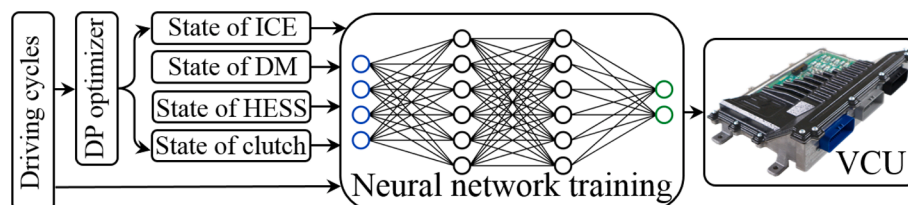


Fig. 6. Neural network-based DP strategy transfer method.

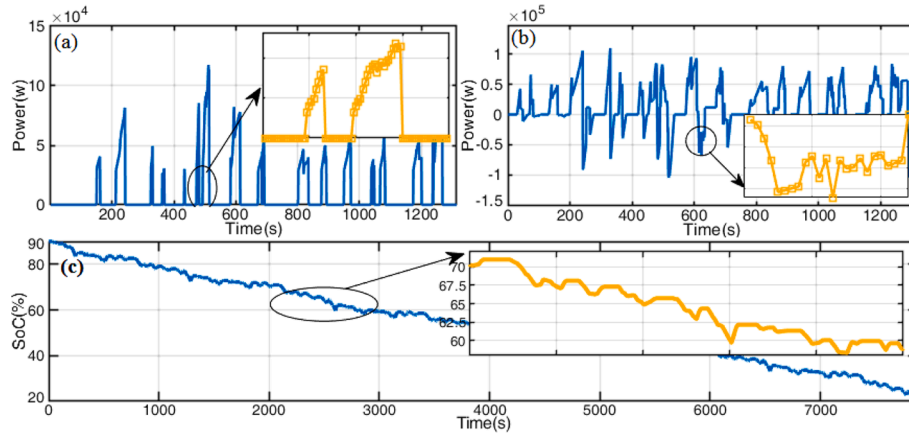


Fig. 7. Power distribution results of the adaptive DP algorithm. (a) the power profile of ICE; (b) the power profile of DM; (c) the SoC profile of the battery.

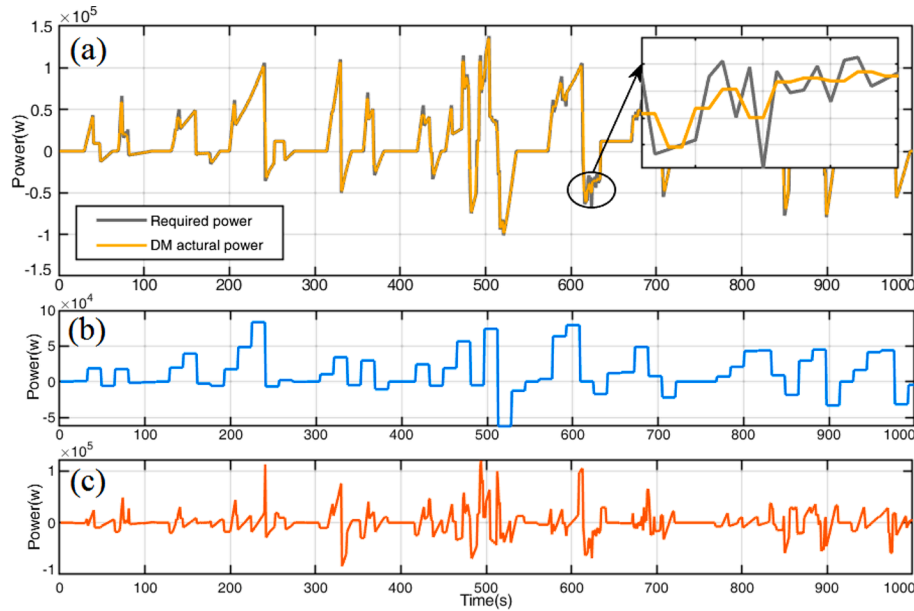


Fig. 8. Power distribution results of the WT algorithm. (a) the PHEV power requirement profile and the actual power profile of DM; (b) the low-frequency component of the original profile; (c) the high-frequency component of the original profile.

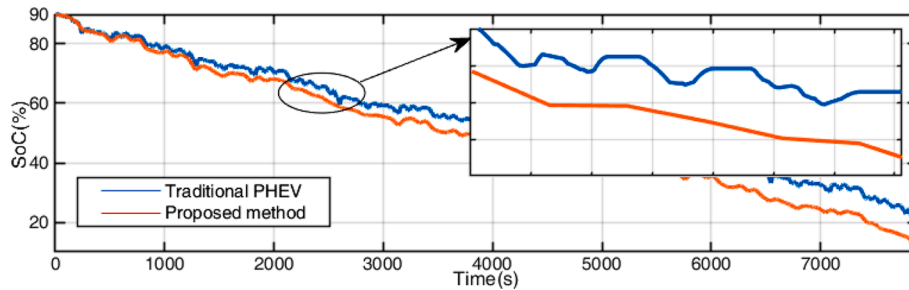


Fig. 9. The comparison of the global SoC profile in traditional PHEV and the proposed method.

thoroughly. Thus, the working points of ICE and fuel cost are not always satisfactory (8.5% higher than traditional PHEV). Compared to traditional Triple-Source powertrain scheme energy management method, the proposed hierarchical optimization framework and adaptive DP algorithm can further optimize the operation of PHEV, the working points of ICE are optimized sufficiently, and the fuel cost has decreased by 10.3% and 6.1%. Meanwhile, the SC system is utilized more reasonably

and sufficiently with the proposed adaptive method, and the battery degradation cost is further reduced to 34358\$ (7.5% and 28.6% compared with traditional PHEV configuration and traditional control algorithm). The win-win relationship between fuel economy and battery longevity enables better total performance. As illustrated in the table, the total economy of the proposed PHEV EMS is improved by 11.1% compared to the traditional method.

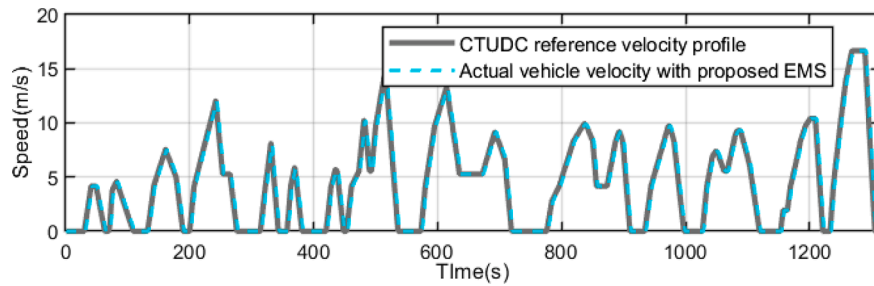


Fig. 10. The velocity following performance of the PHEV in HIL.

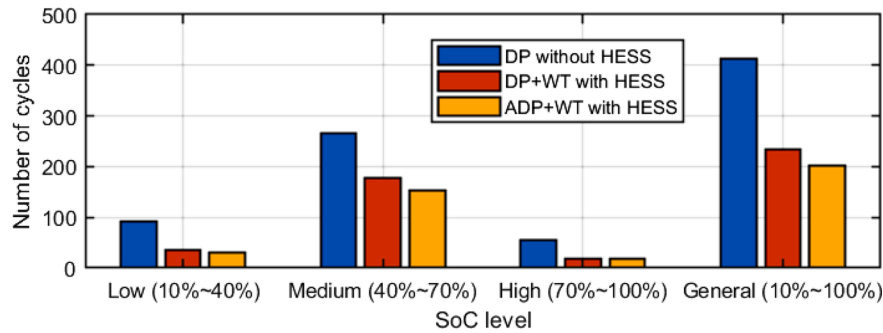


Fig. 11. The comparison of battery degradation phenomenon in different energy management strategies.

Table 2

Comparison of the cost under different PHEV configurations and algorithms.

Parameters	DP method (without SC)	DP method (with SC)	Adaptive hierarchical EMS method
Fuel cost (\$)	29,354	31,850	27,560
Electricity cost (\$)	11,631	13,836	15,364
Battery degradation cost (\$)	48,132	37,125	34,358
SC cost (\$)	0	2268	2268
Total cost (\$)	89,117	85,079	79,950
Total economy (%)	100	95.47	88.92

5. Conclusions

The hierarchical optimization technique is employed in this study to derive a win-win EMS between fuel economy and battery longevity. The HIL experiment results revealed that the proposed method coordinates the operation of ICE, DM and HESS effectively. Compared with conventional PHEV, the Triple-Source powertrain scheme reduces the battery degradation cost significantly (22.9%), the reason is that the SC system cooperates with the battery, thus mitigating the working pressure of the battery system. Furthermore, with the proposed adaptive power distribution algorithm, the fuel cost and battery aging cost are reduced by 6.1% and 28.6%. The reason is that the proposed method can further optimize the working efficiency of ICE, DM and HESS by using the feedback signal generated by the integrated cost quantification model. Overall, the introduction of SC system and the hierarchical energy management strategy improve the total economy of PHEV effectively. The results from this paper justify the effectiveness and economic performance of the proposed method as compared to conventional ones, which will further encourage the promotion of PHEVs.

Future work can be conducted on the following two aspects:

- 1) The proposed energy management method is verified on an ICE-battery hybrid electric bus, however, limited by simulation environment, the change of vehicle cross weight caused by the use of SC and DC/DC converter is not considered. Future work can be

conducted on establishing a simulation platform for Engine-Battery-Supercapacitor hybrid powertrains to verify the performance of triple-source PHEV.

- 2) In the real-world, to enable the real-time hardware application of the developed energy management strategy, the vehicle speed needs to be predicted in advance. But in this paper, we assumed that future vehicle speed information can be predicted and estimated accurately as we mainly focus on suppressing the battery aging phenomenon and improving total economy in PHEV energy management. Future work can be conducted on studying the predictive control energy management method.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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