

Review of Energy Storage Technologies for Extended Range Electric Vehicle

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Abstract

Extended range electric vehicle (EREV) as one type of new energy vehicle (NEV) can reduce emission compared to the traditional fuel vehicle, and also can increase the driving range compared to the pure electric vehicle (PEV), so it has recently become the focus of considerable attention among vehicle manufacturing companies and research institutions. This paper mainly explores the latest applications of various energy storage technologies for EREV, such as battery, ultra-capacitor (UC), flywheel, fuel cell, solar and hybrid power source (HPS). The characteristics of these energy storage technologies are also presented. It is obvious that the power source for EREV should have simultaneously high energy density and power density through comparative analysis, therefore, the HPS will have a good application prospect. Moreover, several common energy storage systems for EREV are deeply discussed. It is observed that power distribution is difficult to meet the high-efficiency requirements for all multiple operating conditions of vehicle and energy utilization ratio is still in a very low level for the conventional energy storage systems for EREV. In view of their shortcomings, a novel energy storage system for EREV is proposed, and several working modes of this novel energy storage system are described in detail. It can be seen that the novel energy storage system can meet the requirements of energy conversion and storage with high efficiency bi-directional power flow in motor driving system of EREV. Finally, the future development of EREV is forecasted and proposed, we think the future development of EREV will need to focus on low-power, low-emission and even zero-emission, high-efficiency HPS.

Key Words: Extended Range Electric Vehicle (EREV), Energy Storage Technology, Ultra-capacitor (UC), Hybrid Power Source (HPS)

1. Introduction

The petroleum crisis and environmental pollution are becoming increasingly serious with the continued growth of car ownership in recent years. The environmental air pollution caused by vehicle exhaust emissions has in fact been started to catch attention of the world. In November 2016, the European Commission drafted “Clean Energy

for All Europeans” and it claimed that 94% of energy consumption of European transport was fulfilled by petroleum. So the European Commission is calling on the Member States to reduce the use of fossil fuels to reduce contaminant and greenhouse gas emissions [1]. The Survey Report from United Nations showed that the exhaust emission of fuel vehicle accounted for more than 60% of the world’s air pollution. The automotive industry mainly driven by petroleum is facing enormous challenges [2], therefore automotive enterprises have committed to de-

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veloping clean energy vehicles to meet ecological requirements. As one type of new energy vehicle (NEV), extended range electric vehicle (EREV) demonstrates outstanding performance in terms of driving range and energy saving and emission reduction, and has become one of the top priorities of auto manufacturers for future research. EREV works in electric vehicle (EV) mode while electric energy of battery is sufficient, the range extender generates energy only when electric energy of battery is insufficient. Commonly used range extenders include internal combustion engine (ICE)-generator set, fuel cell (FC), battery and so on. Compared to pure electric vehicle (PEV) [3], EREV can effectively solve the problem of insufficient endurance and greatly reduce the pollution caused by exhaust emissions.

In 2016, Tengfeng, one of the Chinese vehicle brands, released a concept EREV which applied the Turbine-Recharging technology. This concept EREV used a single micro-turbine as range extender. The micro-turbine can rotate at a speed of up to 96,000 rpm. The EREV has a maximum power of 768 kW and a driving range of 2,000 km. In March of 2017, HongKong Motors displayed three concept EREVs which were developed by the collaboration of Pininfarina: H600, K550 and K750. These three concept EREVs were equipped with power system of “micro-turbine generator extension + super-battery”, which can deliver a maximum output power of 500 kW and a driving range of 1,000 km. It can be relatively sure that the characteristics of micro-turbine are small in size and weight, and excellent self-starting ability, the energy conversion of a micro-turbine can be more efficient than that of an ICE [4,5]. However, the use of a micro-turbine as a range extender will also face some problems such as high cost, difficulty in large scale mass production, poor stability, and so on. Also in March of 2017, Mazda published a latest patent, a front-wheel-drive EREV was stated in this patent [6], which applied Wankel engine to range extender system. The generator was driven by Wankel engine and provided the required energy for batteries. Because of the higher power density than the same power reciprocating piston engine [7,8], a small Wankel engine is suitable for use as a range extender, but first of all, it should solve the problems of poor durability, fuel economy and emissions.

With the support of government departments, a grow-

ing number of vehicle companies and national laboratories have begun to focus on developing the related technologies of EREV. In [9], working modes and auxiliary power system of the conventional EREV were discussed, through comparisons and discussions, it was concluded that EREV had some advantages such as lower emissions, lower costs, higher fuel economy, etc. The control system of auxiliary power unit (APU) of EREV was modeled in [10] and the dynamic response characteristics and control parameters were obtained by gradually changing engine speed. The influence of APU on fuel consumption was tested at different output powers of APU, this study described the results of test, which indicated that APU had a significant effect on improving energy efficiency rate of EREV. In [11], the modeling methods and applications of various power batteries were reviewed and the advantages and disadvantages of each model were explained, these studies are helpful to understand the performance of battery during charging and discharging processes. The frequently used basic structure and working mode of EREV were presented in [12], a new energy power control strategy of ICE was proposed, the simulation results with typical driving cycles confirmed that EREV can achieve good fuel economy in extended range mode. In [13], fuel consumption model, battery model and power demand model of range extender of EREV were established. Multi-objective performance function of range extender's fuel consumption was optimized by dynamic program algorithm, the configuration and loss coefficient of battery were optimized on the basis of simulation results of a single-objective optimization. In addition, the matching relationships among fuel consumption of APU, different penalty coefficients of state of health (SOH) of battery and loss of SOH of battery were analyzed and discussed.

In summary, it can be seen that most of the published studies were concentrated on one type of electrical energy storage technologies and applications, there is a lack of systematic studies regarding the detailed latest applications and developments of various energy storage technologies for EREV. Therefore, this paper reviews various energy storage technologies for EREV, which can assistant researchers to have a further understanding of EREV. Meanwhile, overview of a novel energy storage system and control methods of EREV is presented.

This paper is organized as follows. After the Introduction Section, various energy storage systems and main features for EREV are explained in section 2. The conventional energy storage systems for EREV are summarized and analyzed in section 3. A novel energy storage system for EREV is described in section 4. Conclusions are summarized in section 5. Prospects and suggestions of EREV's future development are given in section 6.

2. Energy Storage Technologies for EREV

There are various common energy storage technologies for EREV: battery energy storage (BES), ultra-capacitor (UC) energy storage (UCES), flywheel energy storage (FES), fuel cell energy storage (FCES), solar energy storage (SES) and hybrid energy storage (HES).

2.1 Battery Energy Storage Technology

BES technology has become one of the most widely used technologies for EREV. The main types of battery for EREV include Lead-Acid, Ni-MH, LIB (sometimes Li-Ion battery), etc [14].

Although lead-acid battery has a low cost, it has some significant shortcomings, such as heavy weight, large volume, short life cycle, and inability to charge and discharge quickly, which make it gradually eliminated in EREV. LIB is widely used in EREV because of its excellent comprehensive performances such as small size, light weight, high specific power, long life cycle and no memory effect [15–17]. In December 2016, Nissan Motor Company launched a compact EREV “Nissan Note” equipped with a new type of power system [18], which uses a 1.3-liter three-cylinder engine with a fuel consumption of 2.7 liters per 100 km and a 1.5 kWh LIB pack. The mass of LIB pack of Nissan Note is only about 20 kg, and it's volume is smaller than that of the Nissan leaf. Audi has developed “e-tron series”, such as A1 e-tron, A3 e-tron, R18 e-tron and e-tron spyder [19–21]. A1 e-tron uses a 380V/12kWh LIB module consisting of 96 prismatic battery cells, and the total weight of the LIB module is less than 150 kg. The Samsung 94 Ah LIB with a high energy density (0.348 kWh/cell) used in the 2017 new generation of EREV “BMW i3” [22], the total energy of the LIB pack is 34.2 kWh. LIB has also been used in some other typical EREVs such as Nissan Leaf,

Chevrolet Volt and Honda Fit. The NEVs of Toyota Motor will adopt LIB instead of Ni-MH battery [23,24]. It can be seen that LIB will become one of the most promising batteries for next generation of NEV [14]. But, there is no doubt that LIB also has some disadvantages, for example, cost of LiCoO_2 for the anode material is high, the special protective circuit must be used to avoid over-charge and over-discharge. In addition, although the battery overall usage cost of EREV is about 40% of PEV, this will also result in a higher vehicle price than the conventional fuel vehicle. Moreover, the number and weight of batteries used in EREVs are still large, there is a considerable potential to reduce the quantity and weight of batteries used for EREV in the future, so the optimized design of the battery pack has been one of the main research focuses [25]. Also, the battery of EREV is almost always working under heavy load, which leads to a pronounced increase in the energy loss and a decrease in the life cycle of battery, therefore, the battery thermal management (including both heating and cooling) becomes more critical and should be one of the focuses for future research [22]. When the ICE-generator set is working, if the power generated by the ICE-generator set does not pass through the battery and directly drives the motor, the energy loss can be significantly reduced, and the battery usage cost can be further reduced, thereby energy saving and emission reduction can effectively be achieved. More importantly, the potential danger of using high energy density battery can be effectively avoided, so the method design of the ICE-generator set directly driving the motor can be further studied, therefore, a more detailed study of design methods of directly driving the motor by the ICE-generator set is required for researchers.

Comparative performances of three common batteries are summarized in Figure 1 [15,16,26]. As can be seen from Figure 1 that the three types of batteries have different features on specific energy, specific power and safety, etc. Although the specific power of LIB is already large, it is still far from meeting the needs of vehicle. It is obvious that battery as the power source of vehicle can not simultaneously meet the requirements of high power and high energy density [27]. Therefore, some studies on improving performances of battery and seeking alternative power sources used for EREV have been conducted by domestic and foreign institutions.

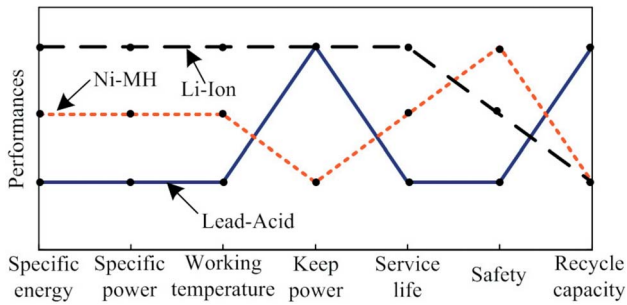


Figure 1. Comparative performances of three common batteries.

2.2 Ultra-capacitor Energy Storage Technology

As a new kind of energy storage component, UC presents considerably higher power density (10~100 times higher) but lower energy density (10 times lower) contrary to conventional battery [28]. UC can provide energy as the vehicle starts and accelerates, and also can absorb the regenerative braking energy. For the features of quick charge/discharge and high power density, UC as a alternative power source can meet the demands of input/output peak power instantaneously, so it is particularly suitable for high repetition rate pulse applications [14], UC has been gradually attracted attention with a good development prospect [28–30]. In HES system of NEV, UC acts as an instantaneous power buffer to efficiently handle large charge/discharge current, which can greatly reduce the current stress on battery, thus the life of battery can be extended. In [31], the working modes of battery/UC HES system were simulated, the study showed that battery/UC HES system had the advantages in voltage and current stability. In this HES system, battery is used to maintain the voltage stability of direct-current (DC) bus, UC provides additional instantaneous high power for the load to mitigate the effects of load changes on the bus voltage. Until recently most automotive enterprises have start to add UC to energy storage system of

vehicle in order to store efficiently braking energy. For example, Mazda 6 applied UC to regenerative braking system, the fuel consumption can be reduced by 10% [32].

UC is applied widely and many research departments are committed to improving its functional performance [33]. For instance, a novel carbonfree UC with larger circulating load for charge/discharge was proposed by researchers of MIT, test results showed that energy storage loss is less than 10% after 10,000 times of circulating charge and discharge [34]. UC can be used as main power source for EREV to replace LIB if its energy density is up to 80 W·h/kg. Overall, at present the UC energy storage system is suitable for pure electric city bus and plug-in hybrid bus (including EREV) [25], its low energy density performance severely limits its application in small cars [35], but with decreasing cost and increasing energy density, the application of UC to replace battery in small cars is bound to become one of the key research topics.

2.3 Flywheel Energy Storage Technology

FES system has the characteristics of fast charge/discharge, clean and high efficiency, and it can be charged/discharged infinitely [36]. The technical characteristics of three energy storage components: flywheel, battery and UC are shown in Table 1 [37,38].

As a kind of short-term energy storage system, FES system cannot be used as the main power source of vehicle, therefore FES system with high power density is often used as APU for vehicle. The common structure of FES system is shown in Figure 2, while the vehicle brakes, FES system absorbs the regenerative braking energy, when the vehicle needs to accelerate, FES system and battery together provide energy for vehicle. so the larger current stress on battery can be reduced, and the stability of energy storage system can be improved.

Many automotive enterprises have paid more atten-

Table 1. Technical characteristics of three energy storage components

Energy storage component	Flywheel	Battery	UC
Cycle efficiency (%)	> 90	> 90	> 90
Cost (\$/kwh)	2000~5000	50~500	1000~5000
Power density (w/kg)	5000~10000	50~2000	1000~18000
Energy density (wh/kg)	100~200	50~300	2~15
Cycles (×1000)	> 1000	0.2~4.5	500~1000
Operating temperature (°C)	Wide range	-20~60	-40~70

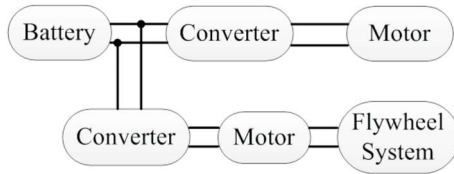


Figure 2. Structure of Flywheel HES System.

tion to FES system [38]. For example, Volvo and Jaguar have used FES system in their new vehicles. The concept of applying flywheel to recycle energy for passenger cars and racing cars was proposed in 2000 year [39]. For instance, Willigams F1 racing cars used FES system to store regenerative braking energy. In 2013, FES system was used in Volvo s60 to store regenerative braking energy efficiently, which can output maximum power of 58.84 kW and reduce 25% fuel consumption [40]. In [41], an optimization method of a novel FES system for HEV was proposed, the results showed that the novel FES system was more suitable for regenerative braking because of its high power density and energy density. FES system can also be used as a power buffer in energy storage system of EREV.

It can be seen that the energy density of FES system is not large enough for vehicle, so it still can not be applied as the main power source for EREV applications

[42]. The energy storage performance of FES system mainly relies on motor/generator unit. In addition, FES system as the range extender for EREV has some disadvantages, such as high loss of rotor, low efficiency and complicated control system.

2.4 Fuel Cell Energy Storage Technology

FC is a clean and efficient energy storage device, which has many advantages: high power generation efficiency, high energy density, little environmental pollution and so on. The common FCs mainly include: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), proton exchange membrane fuel cell (PEMFC) and direct alcohol fuel cell (DAFC) [43,44]. The main technical characteristics of various FCs are shown in Table 2 [45–47].

PEMFC as a commonly used type of FCs in EREV has the advantages of high energy conversion rate, high power density and good development prospects [48]. In March of 2016, Honda launched a FC vehicle “Clarity Fuel Cell”, which adopted the new generation of PEMFC and its extended range can reach 750 km. The Clarity FC stack combines hydrogen molecules with oxygen molecules extracted from air to form water molecules. The

Table 2. The main technical characteristics of various FCs

Type	AFC	PAFC	MCFC	SOFC	PEMFC	DAFC
Working temperature (°C)	50~200	100~200	650~700	800~1000	25~100	25~150
Fuel type	Hydrogen	Reformed gas	Pure Coalgas; Natural gas; Reformed gas	Pure Coalgas; Natural gas	Hydrogen; Reformed gas	Methyl alcohol; Ethyl alcohol
Power (kw)	20~100	200~10000	100~5000	25~5000	0.1~200	0.1~10
Fuel efficiency (%)	65	40~45	50~55	50~60	40~50	30~45
Life Span (×1000 h)	3~10	30~40	10~40	8~40	10~100	1~10
Advantages	Quick start; High efficiency	Moderate; Reaction	High efficiency; Diversified fuel; No pollution	No material corrosion; Various applicable fuel	High energy density; Quick start; High power density	Simple structure; Easy to store
Disadvantages	Requirements for high purity of fuel	Low power density; Slow start; High corrosion of electrolyte	High working temperature	High working temperature; Slow start	High cost	Low energy conversion rate; Quick performance decay; High cost

Clarity's energy storage system also contains a LIB pack which uses to store and release electricity captured during regenerative braking, and to buffer the excess electricity generated by the hydrogen FC. But PEMFC mainly uses Pt as the catalyst, however Pt is comparatively expensive, which is one of the main reasons that PEMFC has not yet been widely applied in NEVs [49,50]. Recently, Magna has developed a FC-EREV that combines the fast filling hydrogen fuel of FC and zero-emission of EV, the FC-EREV can drive 70 km at EV mode and 350 km at extended-range mode.

As shown in Figure 3, the structure of FCES system for EREV mainly includes battery, converters, fuel tank, motor and power distribution unit. The battery normally powered the vehicle in running a short distance. When energy of the battery is not enough to support the vehicle for long distance, FCES system starts to work and provide required energy for vehicle, and it also can charge battery during this process. When the vehicle brakes, the battery can absorb the regenerative braking energy.

The key technologies of FC-EREV mainly include: electric motor and its control technology, FC system, high-pressure hydrogen storage method, hydrogen supply system, and hydrogen safety [51]. And hydrogen demand estimation is a technical difficulty [52]. In order to solve critical issues, Toyota has reduced the cost by increasing the power output density (3.1 kW/L) of the FC stack to achieve miniaturization and high performance [53]. Using a three-layer structure of carbon fiber reinforced plastic (CFRP), the hydrogen storage tank can withstand a high pressure of 70 MPa [54,55], which increases the hydrogen storage capacity while reducing the weight and volume. Hyundai Motor's FC system does not require compressed air and consumes a normal atmosphere [56,57], so efficiency is increased by half. Since there is no air compressor, the noise is greatly reduced.

It can be clearly seen that the FC technology is not

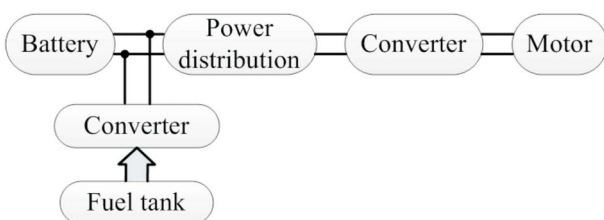


Figure 3. Structure of FCES system for EREV.

readily mature enough, the supporting facilities and the use environment are still not perfect, the application and promotion of FC-EREV are not as fast as LIB-EREV, which will be a long-term development process.

2.5 Solar Energy Storage Technology

SES system is favored by vehicle companies for the performances of clean, safety and economic. The study on efficient and stable SES system has become one of the key points for many automobile enterprises. In [58], the charge/discharge characteristics of solar cell were discussed when it was used in plug-in hybrid electric vehicles, the results showed that electricity generated by the photovoltaic panel could partially meet the needs of the plug-in hybrid electric vehicle. A novel comprehensive energy storage system for EREV was proposed in [59], as shown in Figure 4, the energy storage system consists of solar cell, FC and LIB, it is compared with the energy storage system composed with FC and LIB on the conditions of different operating parameters, different structure designs and different light intensities. The results showed that the addition of solar cell to the energy storage system of EREV could improve the energy efficiency. In [60], Thomas L. Gibson's team used energy produced by SES system to generate hydrogen for FCEV. A comprehensive mathematical model was developed to test the efficiency of solar energy electrolysis devices, the results indicated that the efficiency of solar energy electrolysis devices to generate hydrogen was 12.4%, which could provide enough hydrogen for FCEV. Similarly, it is also a good scheme for range extender of EREV.

How to improve the conversion efficiency of SES system and how to use SES system as the main energy system for EREV have become the key points of further studies. There are some EREVs that use SES system as range extender of energy storage system to provide energy for battery. For example, a concept vehicle named as Luciole was designed by Keio University, Japan. High

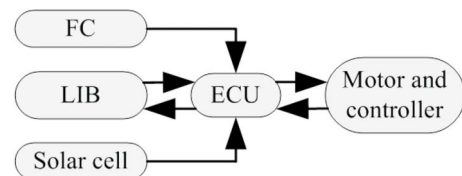


Figure 4. A novel comprehensive energy storage system for EREV.

efficient PV Panel is installed on the top of the vehicle, and it can charge auxiliary battery with voltage of 12 V, the auxiliary battery can also charge the main energy supplying battery when it is full charged. When the main energy supplying battery is full charged, the vehicle can run 800 km. Besides providing energy for power system, solar cell also can be used for vehicle interior electrical units to lift and descend window glasses, or keep proper temperature of vehicle.

2.6 Hybrid Energy Storage Technology

Each type of energy storage technology has its own advantages. It also can be seen that one type energy storage system can not satisfy the requirements of power density and energy density simultaneously. HES system can integrate the advantages of different energy storage technologies. In [30], a HES system consisting of battery and UC was proposed. As shown in Figure 5, battery and UC are respectively connected to DC bus through a bi-directional DC-DC converter. The simulation and experiment results showed that this HES system could effectively suppress the impact to DC bus caused by load mutation. But this type of energy storage system has some disadvantages such as the needs for multiple controllers and complex control algorithms.

In [61], another type of HES system composed with battery and UC was studied. Battery works as main power source to provide sustained energy for load, UC works as auxiliary unit to provide energy in acceleration mode and absorb energy in regenerative braking mode. Test results showed that the HES system had better energy-saving and higher efficiency than single power source. In [62], a HES system consisting of FC and UC was proposed. As shown in Figure 6, FC (as main power source) is connected to the system bus via a one-way DC-DC converter, UC (as auxiliary transient power source) is connected to the system bus via a bi-directional DC-DC power converter. It is shown that the HES system can breakthrough

the limitation of single power source and improve the efficiency of power system.

At present, FCEV usually adopts HES system which consists of FC and auxiliary power source. FC provides continuous power and it can work together with auxiliary power source when the high power is needed instantaneously. The regenerative energy can be stored in auxiliary power source temporarily.

A HES system composed by FC, battery and UC is indicated in Figure 7. In this HES system, FC, battery and UC provide energy for motor together, which can output energy stably. The battery normally powered the vehicle, when energy of the battery is not enough to support the vehicle for driving, UC or with the battery provides required energy for vehicle, when the energy of battery is not sufficient, FCES system starts to work and UC assists FC to provide required energy for vehicle. In this structure, the advantages of each power source can be fully utilized.

HES system is composed of main power source and APU, they can work together when the high power is needed instantaneously. The regenerative braking energy can be stored in APU. In this structure, the advantages of each power source will be utilized. And for EREV, it is the application of different power source as optimized as possible used in range extender. Therefore, applying HES system to EREV has become a very superior scheme.

It can be sure that the application of HES technology in EREV will receive considerable research attention. More attentions should be focused on the study of power distribution and energy utilization ratio of HES system.

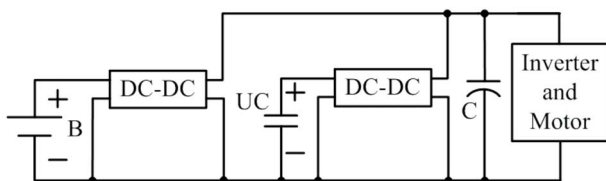


Figure 5. A HES system composed by battery and UC.

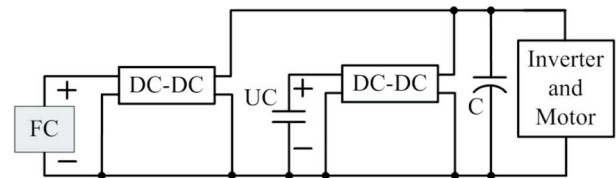


Figure 6. A HES system composed by FC and UC.

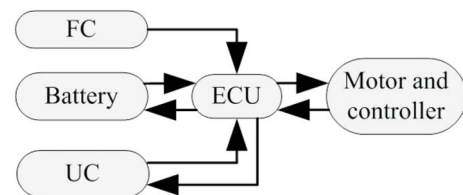


Figure 7. A HES system composed by FC, battery and UC.

Optimal power allocation mechanism and power flow control strategy of HES system are the key technical problems to be solved.

3. Traditional Energy Storage Systems for EREV

As shown in Figure 8, the traditional energy storage system for EREV mainly consists of a small ICE-generator set, battery and a drive motor. When the energy of battery is sufficient, the energy only provided by battery, if there is not enough energy in battery, the range extender starts to charge battery. In addition, the battery of EREV can be charged by external plug-in cable and it can meet the requirements for daily driving with the economical and environmental features.

Performance comparisons among EREV, EV and HEV (includes parallel hybrid electric vehicle (PHEV) and series hybrid electric vehicle (SHEV)) are shown in Figure 9 [3]. Compared to EV, EREV adds an additional APU (a ICE-generator set), but it has a longer driving range. Compared to HEV, EREV has a simpler structure system, more reliable performance and less cost. From the current technical environment and market demand, it can be seen that EREV is one of the most promising products. However, EREV needs to convert power frequently between the main power source and the auxiliary power

source, which reduces system efficiency [63,64]. Therefore, how to optimize the economical efficiency while ensuring its power performance has become one of the key issues for EREV.

There are three working modes of traditional energy storage system for EREV:

(1) Working Mode 1: EV mode

The vehicle is powered only by battery when it's energy is sufficient. The energy flow path is shown in the following Figure 10(a).

(2) Working Mode 2: extended range mode

As shown in Figure 10(b), the vehicle is powered by battery, but when battery energy is not sufficient to provide required energy for driving vehicle, the range extender system starts to charge the battery. The ICE works in a comparatively ideal state, therefore the output power and the torque can be kept stable to make a rather high efficiency.

(3) Working Mode 3: energy recovered mode

The motor is working as generator and generates electric energy to charge battery. The energy recovered working mode is shown in Figure 10(c).

It can be seen that there are several disadvantages of traditional energy storage systems for EREV:

(1) When the power is only provided by battery, the power source needs a high voltage while the required power is increased instantaneously. It will enlarge the vol-

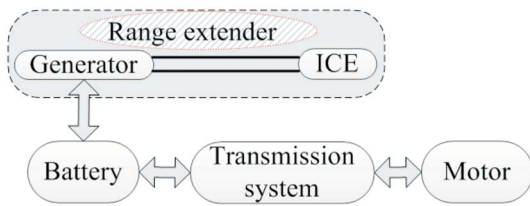


Figure 8. The traditional energy storage system for EREV.

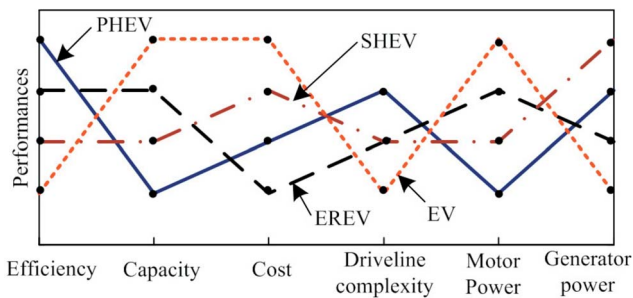


Figure 9. Performance comparisons among EREV, EV and HEV.

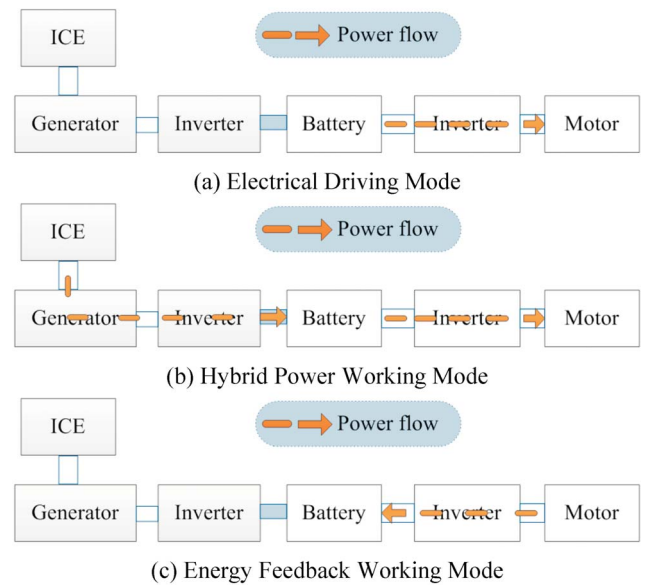


Figure 10. Working modes of the traditional energy storage system for EREV.

ume of energy storage system.

- (2) The voltage of power source needs to be higher than back electromotive force (EMF) of the motor. The changing range between back EMF and power source voltage is rather big when the rotation speed changes greatly, which reduces the conversion efficiency.
- (3) In energy recovered mode, the back EMF can not be boosted to the voltage of power source when the speed is too low, therefore quite little energy can be recovered. However, when the speed is too high, the certain transformer ratio of power converter (or inverter) will cause the recovery of braking energy in a low efficiency.

From the rigorous review of the disadvantages of the traditional energy storage system for EREV, a novel energy storage system for EREV is presented in the next section for optimizing the design of energy storage system.

4. A Novel Energy Storage System for EREV

A novel energy storage system for EREV was proposed by the research group that the authors belonging to [65]. The system consists a HPS, a bi-directional DC-DC power converter (BDPC) and an H-bridge converter, as shown in Figure 11.

The HPS includes UC and battery banks. UC banks as high efficient charge/discharge power buffer unit are added to the system. UC banks can temporarily store the energy generated by ICE-generator set and absorb the regenerative braking energy. The structure of power plant for EREV containing the novel energy storage system is shown in Figure 12.

Several working modes are presented as follows:

- (1) Working Mode 1: electrical driving mode

When the battery energy is sufficient, the required

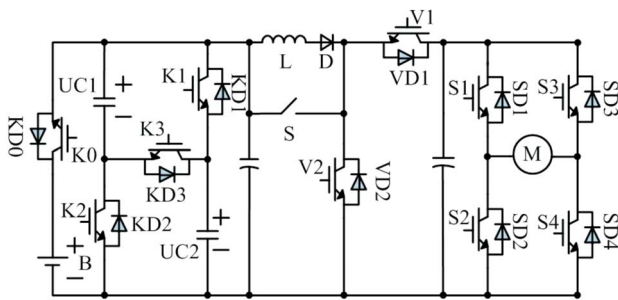


Figure 11. The novel energy storage system for EREV.

energy of EREV is only provided by battery. The energy flow is indicated in Figure 13(a).

- (2) Working Mode 2: independent working mode

When the control unit detects that the battery energy can not meet the requirements of long distance driving, ICE-generator set can be operated to generate electricity. The energy can be pre-stored into the power buffer unit. The energy flow is shown in Figure 13(b).

- (3) Working Mode 3: hybrid power working mode

Battery and power buffer unit can provide energy together when the vehicle accelerates frequently. The energy flow path is shown in Figure 13(c). Battery can output stable power while the extra power is supplied by power buffer unit. When the energy of battery is very low, ICE-generator set and battery can work together to provide the required energy for longer distance driving. The energy flow is shown in Figure 13(d).

- (4) Working Mode 4: energy feedback working mode

The energy flow path is shown in Figure 13(e). When the recovered energy is too much, the energy can be fed to battery, which can increase the energy efficiency.

In this novel energy storage system for EREV, the structure of HES system can be designed in various types. To take the example of the simplest direct parallel structure, the current changes of HES system are shown in Figure 14. When the load current changes randomly, only low current flows through battery, UC can undertake the majority of the load current. There is a gentle and smooth current exchange between UC and battery. It indicates that UC works as power buffer unit in this direct parallel structure and it can make effective adjustment to the power of battery, which can greatly extend the battery life.

Comparing to the traditional energy storage systems for EREV, the proposed novel energy storage system can be applied for EREV with several advantages:

- (1) UC is paralleled to battery by power converter, which can make full use of the large power density of UC and large energy density of battery. It can control en-

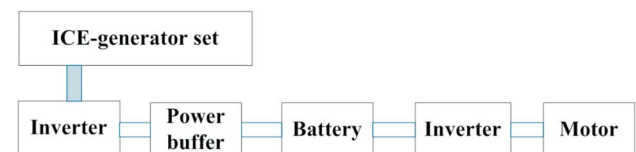


Figure 12. Structure of power plant for EREV containing the novel energy storage system.

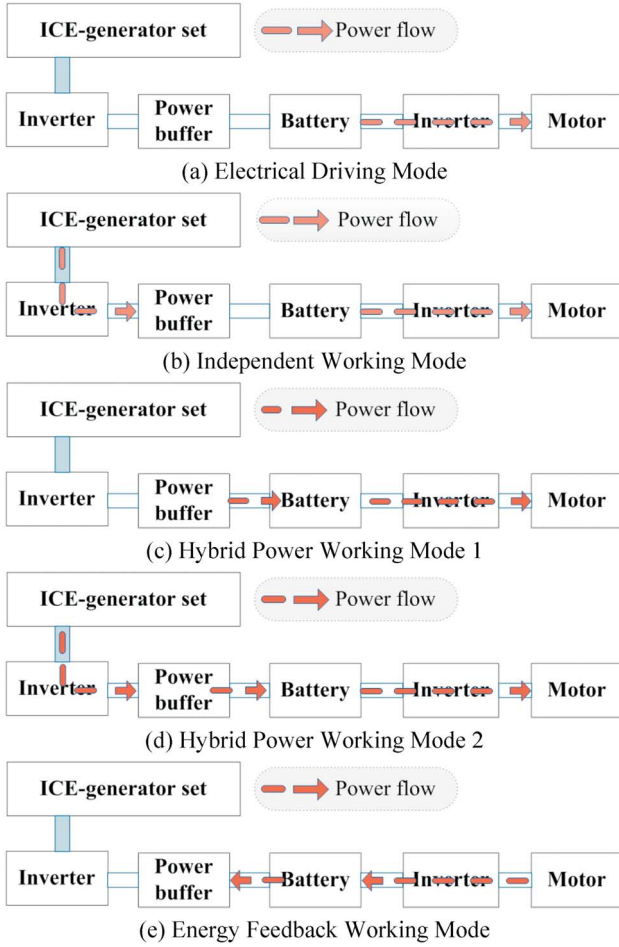


Figure 13. Working modes of the novel energy storage system for EREV.

ergy flow reasonably and effectively. When the instantaneous power is overlarge, the damage of battery can be avoided.

- (2) Two regenerative braking modes can be realized. It has higher transmission efficiency of energy flow when the speed of the vehicle is changing greatly.
- (3) As the auxiliary energy supply, UC can improve the charge/discharge performances of energy storage system and meet the requirements of bi-directional high-efficient energy flow.

From the previous studies of the proposed novel energy storage system, we recognize that the focus of future research is the comprehensive control of each subsystem. The key scientific issues that we need to solve are the optimization design of power flow control strategy that can realize intelligent control and the optimum utilization of energy of HPS.

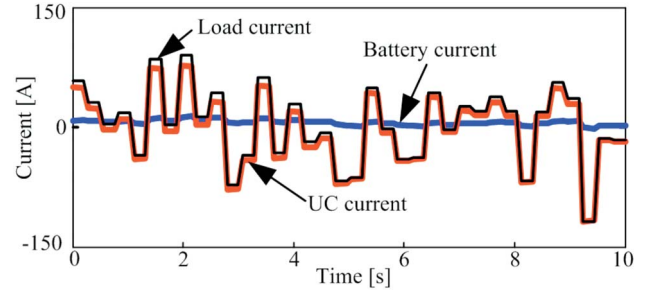


Figure 14. Current changes of direct parallel structure of UC and battery.

5. Conclusions

- (1) The latest applications of various energy storage technologies for EREV are presented, such as battery, UC, flywheel, FC, solar and HPS. Advantages and disadvantages of each energy storage technology are analyzed. Battery can not simultaneously meet the requirements such as high charge/discharge capacities and long life cycle. UC as a new type of green energy will be widely used in vehicle in the future. Flywheel is mainly used for regenerative braking and can not be used as the main power source of vehicle. The catalyst that used in FC is very expensive, moreover, the support facilities still can not fulfill the needs of FC applications. Solar is affected huge by the environment, so it is still in the development and testing phase. HPS has the superior performances such as energy-saving, high power density high energy density, high efficiency.
- (2) Comprehensive and systematic discussions of several conventional energy storage systems for EREV are discussed, it can be seen that these existing conventional energy storage systems for EREV can not meet a high efficiency of power flow over the full operation range.
- (3) A novel energy storage system for EREV is proposed. The structure design and working principle of this novel energy storage system are presented, and advanced features of this novel energy storage system are also highlighted.

6. Recommendations

- (1) Energy storage technology of EREV is a strongly

comprehensive and multidisciplinary technology, it has a close relationship with Material Discipline and Chemical Discipline. So researchers should be seeking a breakthrough in the related disciplines.

- (2) A variety of energy storage technologies for EREV applications have different advantages and disadvantages, so hybrid energy storage technology for EREV should become an important research topic.
- (3) In order to effectively control energy flow, the optimal structure design and excellent control strategy of energy storage system for EREV should become one of the important research topics.
- (4) The novel energy storage technologies for EREV can be further explored.

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