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Review:

Development of electric construction machinery in China: a review of key technologies and future directions*

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Abstract: The issues of energy shortage and environmental pollution have accelerated the electrification of construction machinery (CM) industry globally. In China, the amount of electric construction machinery (ECM) has been growing across the industry. The sales of ECM are estimated to reach 600 000 vehicles by the end of 2025, while the total demand for battery power will reach 60 GWh. However, the development of ECM still faces critical challenges including reliable power supply and energy distribution among various components. In this review, we primarily focus on important technological breakthroughs and the difficulties faced by the CM industry in China. An overview of ECM including classification and characteristics is given at the beginning. Next, the selection of key components such as the electric motor and the energy storage units, and the control strategy in the pure electric drive system are discussed. The characteristics of the hybrid electric drive system such as structure design and power matching are analyzed in detail. The battery management system (BMS) is critical to ensure appropriate battery health for reliable power supply. Here, we extensively review technical developments in various BMSs. In addition, we roughly estimate the national total of CM emissions and the potential environmental benefits of employing ECMs in China. Finally, we set out future research directions and industrial development of ECM.

Key words: Construction machinery (CM); Electric drive system; Battery management system (BMS); Energy recovery; Electrification
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1 Introduction

As global energy shortage and environmental pollution become increasingly prominent (Tong et al., 2021), many developed countries have planned bans on the sale of new petrol and diesel vehicles in favor of electric models. In China, a similar ban has also been put on the agenda by the Ministry of Industry and Information Technology. As a result of China's rapid infrastructure development, construction machineries (CMs) (e.g. forklift, excavator, and crane) powered by fossil fuels have been widely used in many industries and have consumed a vast amount of energy, and significantly contributed to various environmental issues in China over the decades (Lin et al., 2017b; Tong ZM et al., 2019). In Table 1, CM sales and market share of the top 30 companies worldwide are summarized. Five Chinese CM manufacturers

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(XCMG, SANY, Zoomlion, LiuGong, and Lonking) account for 16.3% of the global market, with total construction equipment sales reaching $33 billion. From 2000 to 2019, CM sales in China have been growing steadily (Fig. 1a). The sales volume of CM, including excavator, loader, crane, road roller, bulldozer, land leveler, and paver, from 2006 to 2019 is presented in Fig. 1b. As of 2019, the total number of CMs in China was 8.86 million.

Table 1 CM sales and market share of the top 30 companies worldwide (KHL, 2020)

No.	Company	Country	CM sales (million dollars)	Market share (%)
1	Caterpillar	USA	32882	16.20
2	Komatsu	Japan	23298	11.50
3	John Deere	USA	11220	5.50
4	XCMG	China	11162	5.50
5	SANY	China	10956	5.40
6	Volvo Construction Equipment	Sweden	9381	4.60
7	Hitachi Construction Machinery	Japan	8989	4.40
8	Liebherr	Germany	8565	4.20
9	Doosan Infracore	Korea	6689	3.30
10	Zoomlion	China	6270	3.10
11	Sandvik Mining and Rock Technology	Sweden	5934	2.90
12	JCB	UK	5500	2.70
13	Terex	USA	4353	2.10
14	Epiroc	Sweden	4181	2.10
15	Oshkosh Access Equipment (JLG)	USA	4079	2.00
16	Metso	Finland	3635	1.80
17	Kobelco Construction Machinery	Japan	3371	1.70
18	Kubota	Japan	2866	1.40
19	LiuGong	China	2820	1.40
20	CNH Industrial	Italy	2768	1.40
21	Sumitomo Heavy Industries	Japan	2671	1.30
22	Hyundai Construction Equipment	Korea	2450	1.20
23	Manitou	France	2346	1.20
24	Wacker Neuson	Germany	2131	1.10
25	Palfinger	Austria	1966	1.00
26	Tadano	Japan	1959	1.00
27	Manitowoc	USA	1834	0.90
28	Lonking	China	1812	0.90
29	Fayat Group	France	1726	0.90
30	Hiab	Finland	1513	0.70

Electrification of CMs offers many benefits including emission reduction, decreased noise level, lowered operation cost, and improved safety. The energy sources for CMs have been gradually shifting from fossil fuels to clean and renewable energy. As battery technology has matured and costs have dropped, many manufacturers in developed countries have been developing and releasing electric and hybrid CM models (Table 2). For example, Volvo Construction Equipment (Volvo CE) started to focus on compact all-electric CMs without large power demand. They released several models of electric excavators (ECR25, EC55, and EC230) and wheel loaders (L25H) between 2019 and 2020. Doosan Bobcat announced its first fully battery-powered mini-excavator (E10e) in 2019 and entered the European and USA markets with success. Caterpillar has introduced both all-electric and diesel-electric models in recent years, including the world's first large-scale 25-t all-electric excavator (323F Z-line) with a 300 kWh battery pack, a diesel-electric wheel loader (988K XE) that utilizes a highly efficient generator-invertor-motor electric drive to replace the torque converter and transmission, and an electric load-haul-dump (R1700 XE LHD) for underground mining, bringing benefits including the need for less ventilation infrastructure, emission reduction, less heat generation, and lower operating costs. Komatsu has followed the electrification trend in the CM industry closely and it has a long history in hybrid CM technologies. The company released the world's first hybrid 20-t hydraulic excavator (PC200-8E0) back in 2008. By the end of 2016, the global sales of Komatsu's hybrid CM had hit nearly 4000 units. Different from conventional hybrid systems, the Komatsu hybrid electrical system consists of three main components: an electric generator motor, an electric swing motor generator, and an ultra-capacitor with inverter. In 2020, Komatsu launched a new all-electric mini excavator (PC30E-5) in the Japanese market based on its existing expertise of hybrid CM.

In China, electric construction machinery (ECM) has been rapidly developed by major Chinese CM manufacturers since 2015. For example, XCMG has designed different types of CM, such as the electric forklift, electric loader, and electric excavator, and the usage cost of their electric excavator is 60% less than that of a traditional excavator. In 2019,

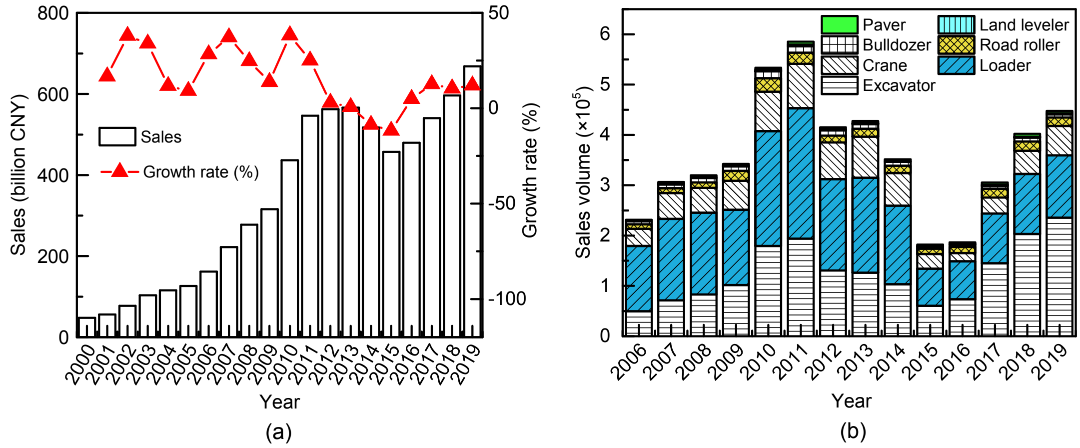

Fig. 1 CM sales and growth rate in China from 2000 to 2019 (a) and CM sales volume by CM type in China from 2006 to 2019 (b) (data source: China Construction Machinery Association)

Table 2 Main ECM products (include hybrid) from top global CM manufacturers

Company	Main ECM product (include hybrid)
Caterpillar	(1) 323F Z-line all-electric excavator; (2) R1700 XE LHD; (3) 988K XE electric loader; (4) D6 XE electric dozer
Komatsu	(1) HB205-2/HB215LC-2, HB335-3/HB365-3 hybrid excavator; (2) PC30E-5 mini all-electric excavator
Volvo	(1) EC55, EC230, and ECR25 electric crawler excavators; (2) L25H electric loader
Doosan Bobcat	E10e electric mini-excavator
XCMG	(1) XE series electric excavator; (2) XC9 series electric loader; (3) XCT25-EV electric crane; (4) XCB series electric forklift truck
SANY	SY16C electric excavator
Zoomlion	(1) ZTC250N-EV electric automobile crane; (2) FB series electric forklift truck
LiuGong	(1) 856H-EV electric loader; (2) 906E-EV and 922F-EV electric excavators
Hangcha	A, AE, X, and XC series electric forklift trucks

SANY proposed a pure electric port tractor that can be driven for 120 km on one charge. In 2020, Zoomlion produced the world's first 25-t pure electric automobile crane, which uses a $LiFePO_4$ battery. LiuGong has applied quick-charge technology to CMs (electric loader and electric excavator), and their batteries can be charged to 80% capacity within 1 h. We have summarized the main ECM products from the top manufacturers in Table 2.

ECMs include electric excavators, electric wheel loaders, electric forklifts, electric bulldozers, electric cranes, and electric road rollers (Fig. 2). They are widely operated in various engineering applications and are critical for infrastructure development and manufacturing industry. The most common operating characteristic of an ECM is frequent starting and braking (e.g. the electric wheel loader and electric forklift) and the hauling of heavy cargo (e.g. electric excavator and electric forklift). Therefore, the recovery of gravitational potential energy and swing brake energy is beneficial for achieving higher energy efficiency for many kinds of CM (Filla, 2009; Ovrum and Bergh, 2015; Lin et al., 2017b). Lin et al. (2016) found that the motor-generator unit is more suitable for energy recovery from an excavator than is the accumulator-motor-generator unit. Wang et al. (2016) developed a model predictive controller (MPC) control method for saving the energy of the hybrid electric tracked bulldozer. Simulation technology is used to compare the relative performances of the dynamic programming method and the rule-based control method. Antonelli et al. (2017) designed an energy regeneration system (ERS) to recover the energy of rubber-tired gantry (RTG) cranes to an ultra-capacitor. Minav et al. (2012b) developed an energy regeneration unit used in the lifting system of an electro-hydraulic forklift. The energy regeneration unit is combined with an electric servo motor and a hydraulic pump. Compared to other kinds of CM, the zero-emission pure electric forklift is the best choice for indoor operations (Tong et al., 2018). In addition, it is

Fig. 2 Typical ECM types

(a) Electric excavator; (b) Electric wheel loader; (c) Electric forklift truck; (d) Electric bulldozer; (e) Electric automobile crane; (f) Electric road roller

also important to note the customized design of ECM for special engineering projects.

Electrification has been widely applied to passenger vehicles (Tie and Tan, 2013; Xiong et al., 2014) and has been shown capable of reducing emissions significantly without sacrificing performance. The experience gained from the automotive industry can be utilized to accelerate the development of ECMs. Nowadays, CMs can be used in various operating environments. However, the ECM has still only just entered the exploratory stage. We summarize the most significant differences between the utilization of CM equipment and passenger vehicles:

1. Application scenarios: CM is usually operated in hazardous environments, including hot and humid environments, alpine areas, and dirty and dusty environments. These conditions require that both the electrical system and power source have a robust and adaptive capacity. In contrast, passenger vehicles typically are operated under more favorable circumstances, with comparatively simple requirements for the electrical system and battery (He and Jiang, 2018).

2. Operating conditions: In contrast with electric vehicles, ECMs (e.g. the dump truck, tractor, and mine truck) require a significantly greater amount of power due to their large volume, heavy weight, and extreme load. Further, CM has an extremely broad range of power requirements depending on its operating state (Wang et al., 2017). This means CM needs a robust energy management system to ensure stable energy output and rapid shift between different operating modes. CM is focused on load capability whereas the focus of the passenger vehicle is on mobility.

3. Mechanical construction: CM has more components and thus has more complicated structures than passenger vehicles and thus has additional major engineering requirements in addition to being driven. For example, in contrast to passenger vehicles, the forklift truck has an extra lifting system, which usually consists of a forklift mast, a heavy fork, and a hydraulic system. The hydraulic system contains the components of the reversing valve, pump, and pipe. Furthermore, the excavator has a more complicated lifting mechanism that combines the boom, bucket rod, rocker, connecting rod, bucket, and oil cylinder. To meet its engineering requirements, a rotary system is also required based on the rotary motor, reversing valve, and pipe for the excavator.

As mentioned previously, there are still many unsolved technological problems in the development of ECMs, namely: (1) structural design of the electric system; (2) matching of power parameters; (3) energy distribution and recovery; (4) battery management. This paper aims at providing a comprehensive review of recent progress in ECM development in China and pointing out the benefits and challenges as the ECM market grows. The paper is divided into six sections and is organized as follows: Section 2 discusses the characteristics and key technologies of the pure electric drive system (PEDS). Section 3 describes the structure and power matching technology of the hybrid electric drive system (HEDS). Section 4 introduces the battery management system (BMS) and mainly focuses on battery prognostics and thermal management. Section 5 discusses the cost-benefit of ECM. Section 6 summarizes the current development of ECM and points out the challenges for future research.

2 Pure electric drive system (PEDS)

2.1 Characteristics of pure electric construction machinery (PECM)

The internal combustion engine (ICE) is replaced by an electric motor in PEDS, which makes the operation of PECM very smooth, with less noise and vibration compared with traditional-fuel construction machinery (TFCM) (Lin et al., 2020). Since PECM uses only electric energy as its power source, it can realize zero-emission operation. It has therefore been gradually applied to CMs such as those in forklift trucks and cranes. PECMs are especially welcome in indoor places where there are stringent requirements for emission and noise.

PEDS consists of two critical components: the energy storage unit (ESU) and the electric motor. Their functions correspond to the fuel tank and engine in the TFCM: (1) a store and supply for the energy source and (2) a drive for the CM. The key role in the ESU of TFCM is to monitor the state of fuel (e.g. temperature and flow conditions) (Cao et al., 2014). There are various types of energy storage units in PECM including a lead-acid battery, a supercapacitor, a flywheel or a lithium-ion battery (Hannan et al., 2017).

For the power unit, the engine of a TFCM supplies power by turning chemical energy into mechanical energy. Fossil fuel is atomized and ignited in the combustion zone; the piston is pushed by combustion pressure, and its reciprocating force is transformed into rotary power by the crankshaft (Mourelatos, 2001). Energy is therefore wasted in overcoming friction and in the generation of noise and vibration (Miao et al., 2017; Tong SG et al., 2019). In comparison, the electric motor of PECM provides power by converting electric energy to mechanical energy (Ferreira and de Almeida, 2018). The rotor of the electric motor is driven by electromagnetic forces, and thus the electric motor can output rotary power. The maintenance cost of the electric motor is lower than that of ICE due to its simpler structure. In contrast to the engine, the electric motor produces less noise and vibration, and it can be smoothly operated with high efficiency. However, for some electric motors there still exist issues of high cost or low reliability.

2.1.1 Energy storage unit (ESU)

The ESU is significant as it ensures a reliable power output in CM. The classification of various types of ESUs is shown in Fig. 3 and these are widely applied in various CM applications. The most popular ESU includes fuel batteries (Hosseinzadeh et al., 2013), lithium batteries (Ge et al., 2018; Paul et al., 2020), a flywheel (Li et al., 2020), and an ultra-capacitor (Conte et al., 2014). The primary characteristics of several kinds of energy sources are included in Table 3 and classified in Fig. 4. Lithium batteries have excellent specific energy and energy density, which benefit the lightweight design of CM. In contrast, other kinds of units, like those powered by an ultra-capacitor, need a larger space and greater weight to realize the same level of energy supply. Considering the power demands of the different components in the system and their production costs, it is appropriate to combine lithium batteries with

Table 3 Key characteristics of commonly used ESUs

Performance indicator	Specific power (W/kg)	Specific energy (Wh/kg)	Energy density (Wh/L)	Lifespan (cycle)	Security evaluation	Efficiency (%)
Lead-acid battery	75–300	30–50	50–80	500–1500	Good	<80
Flywheel	400–1500	10–30	20–80	20000	Bad	≤96
Ultra-capacitor	500–5000	2.5–5.5	35	100000	Good	≤95
Lithium battery	250–340	75–200	200–500	2000–10000	Good	≤95

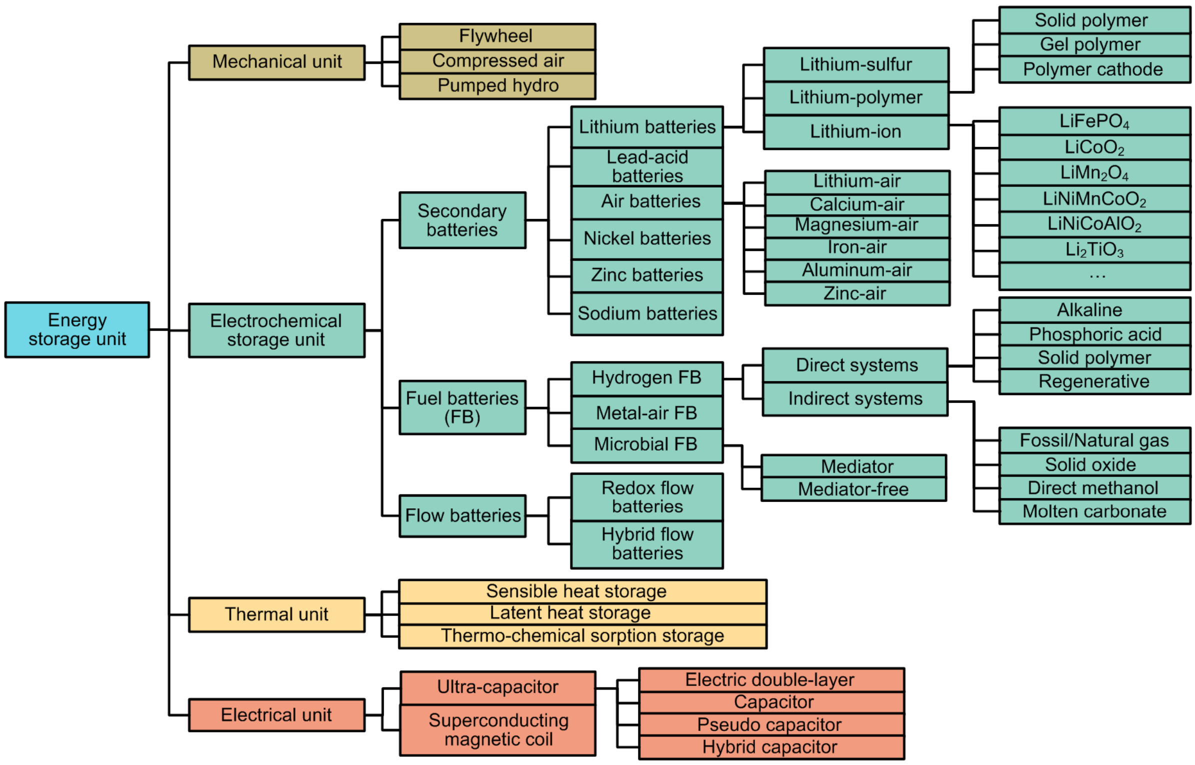

Fig. 3 Classification of ESU according to mechanism and composition materials

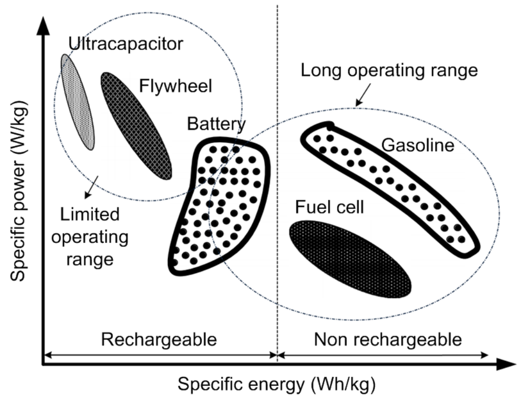

Fig. 4 Specific power vs specific energy characteristics for several normal energy sources. Reprinted from (Kumar and Jain, 2014), Copyright 2014, with permission from Elsevier

other kinds of ESUs (Fig. 3) to develop high-performance and reliable CM (Hsieh et al., 2016). Yi et al. (2018) utilized both fuel cells and batteries to develop ESU to support the electric motor of, for example, an excavator. Fuel cells have also been used as the main power source, and batteries have been used as an auxiliary power source to supplement them. Hosseinzadeh et al. (2013) adopted a hybrid ESU, including the proton exchange membrane fuel cell and a lead-acid battery, to optimize the performance of a forklift truck.

2.1.2 Electric motor

Electric motors can be broadly classified as direct current (DC) or alternating current (AC). Their more detailed classification is described in Fig. 5. Commonly used electric motors include the DC motor, the permanent magnet synchronous motor, the reluctance synchronous motor, and the asynchronous motor. However, the DC motor is not suitable for CM applications due to its complicated structure and unsatisfactory reliability. The reluctance synchronous motor can be applied to CM due to its low cost, high efficiency, and high torque density, and is fabricated without rare-earth materials (Boglietti et al., 2006). However, the noise and vibration caused by torque ripple and radial distortion limit the application of the reluctance synchronous motor. At present, asynchronous motors and permanent magnet synchronous motors are widely used in CMs. The asynchronous motor has a simple structure and thus achieves good reliability and low cost. The permanent magnet

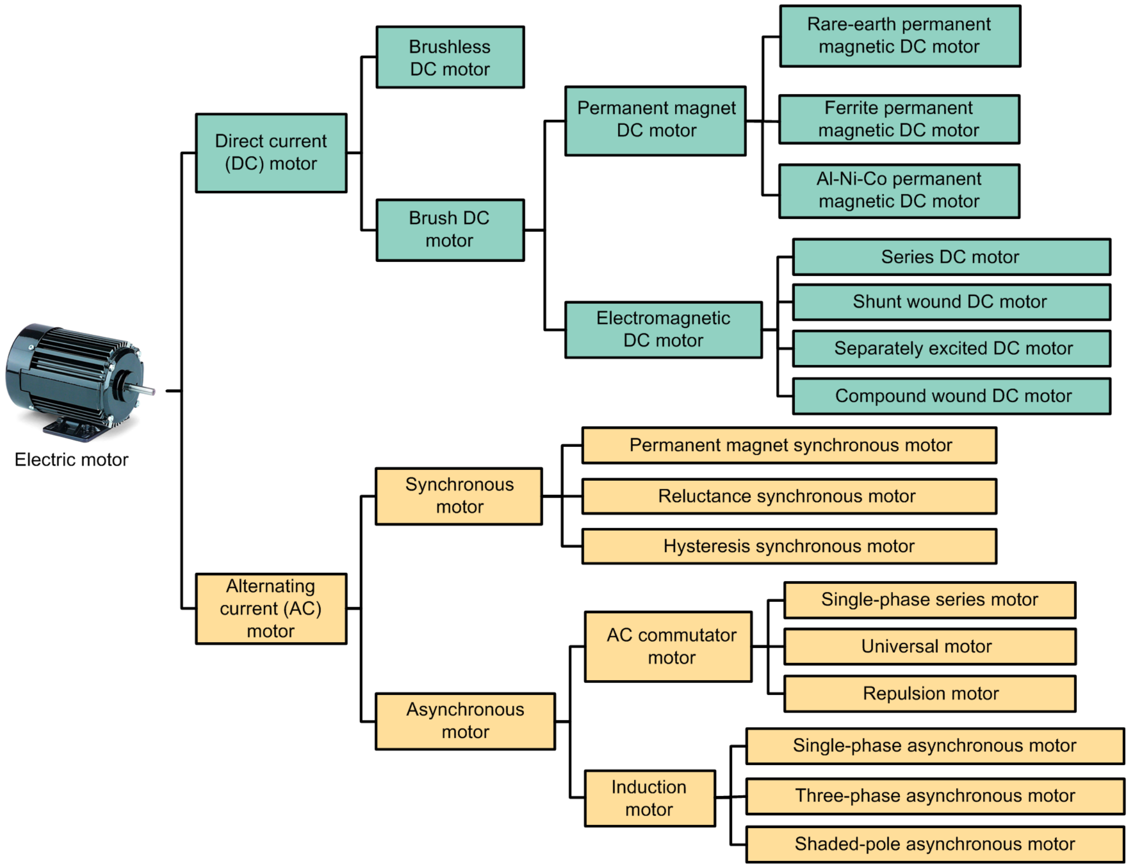

Fig. 5 Classification of the electric motor according to mechanism and composition materials

synchronous motor can only be utilized in a limited space due to its high-power density and torque density (Jacobs et al., 2009). One of the most important considerations in PEDS is to select a suitable type of electric motor that can support the entire electric system and operating conditions (Minav et al., 2012a). Ge et al. (2017) found that consumed power noticeably declined (from 2.05 kW to 0.70 kW) when the variable-frequency electric motor replaced the constant-speed electric motor, indicating the significance of selecting an appropriate electric motor for lowering energy consumption.

2.2 Structures and control strategy of PEDS

The PEDS combines multiple ESUs, an electric motor, and many components such as pumps and valves to achieve complicated functions. In this section, the pure electric hydraulic excavator is used to represent PECM in the examination of the structure and control strategy of PEDS. In Fig. 6, the PEDS of the pure electric hydraulic excavator is depicted in more detail. The main power is output from an electric motor and the variable pump is driven by the electric motor. The electric energy produced is converted to hydraulic energy through the electric motor and variable pump in this process. The mechanisms of the hydraulic excavator are driven by the hydraulic motor and controlled by multiple plunger pumps and reversing valves. Lin et al. (2017a) proposed a two-level idle speed control system that automatically controls the speed of the electric motor. The energy consumption saved is about 36.06% compared with a hydraulic excavator without idle speed control.

The control strategy aims to achieve good performance in fuel economy, emissions, cost, and drivability (Enang and Bannister, 2017). A classification of the commonly used control strategies is provided in Fig. 7 (p.253). In contrast to the optimization-based method, the rule-based method is simple to develop and has low computing cost (He and Jiang, 2018). Hosseinzadeh et al. (2013) utilized the Light, Fast, and Modifiable (LFM) simulation software to

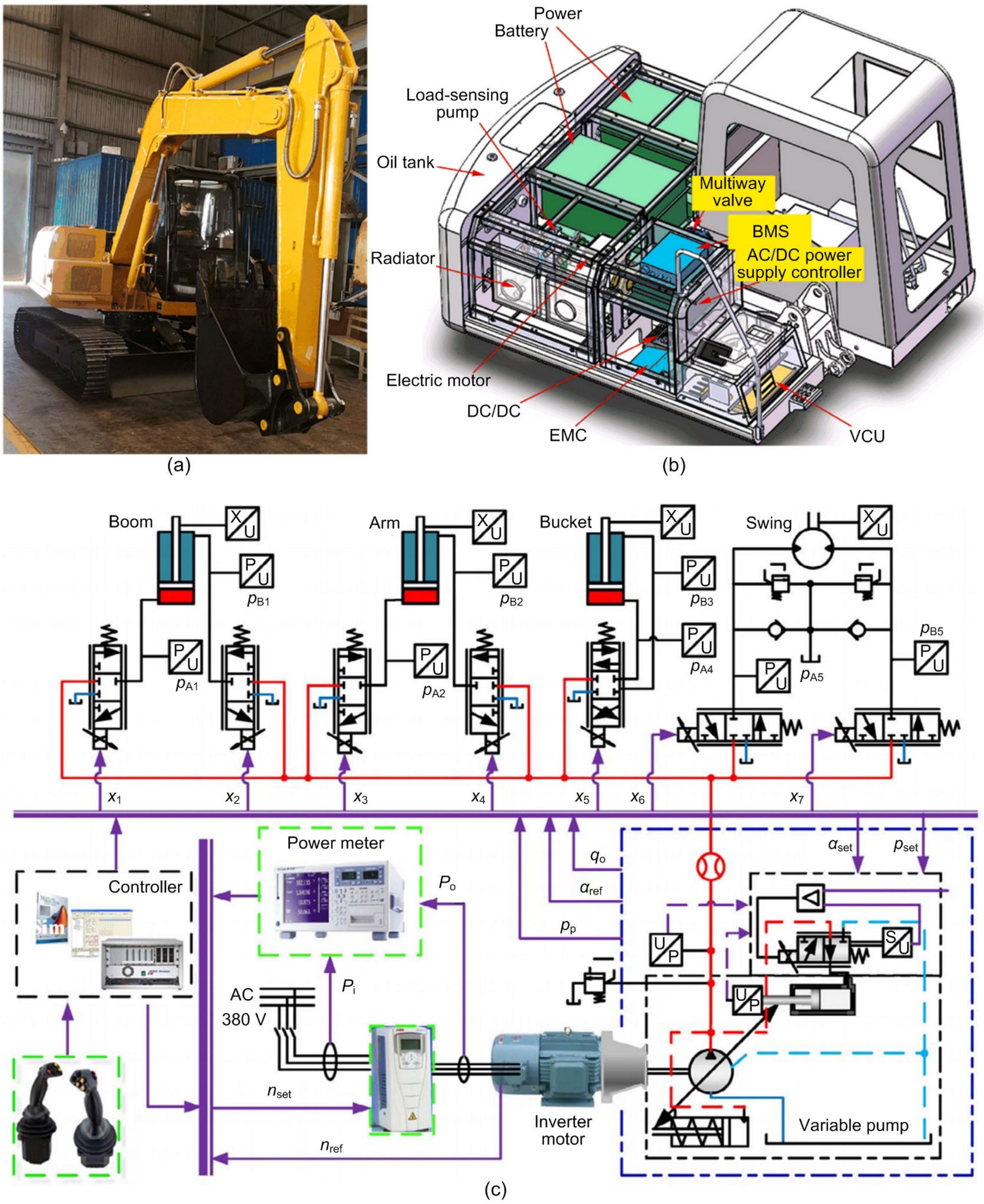

Fig. 6 PEDS of a pure electric hydraulic excavator

(a) Structure of a pure electric hydraulic crawler excavator; (b) System composition of a pure electric hydraulic crawler excavator (reprinted from (Lin et al., 2020), Copyright 2020, with permission from Elsevier); (c) Structure of PEDS (reprinted from (Ge et al., 2017), Copyright 2017, with permission from Elsevier). EMC: electric motor controller; VCU: vehicle control unit; Descriptions of the variables in Fig. 6c refer to Ge et al. (2017)

investigate the performance of two rule-based control strategies in an electric forklift. The ESU of the forklift was combined with a polymer electrolyte membrane (PEM) fuel cell and a lead-acid battery. The first strategy was based on average power consumption, while the second was based on maximum efficiency. The results showed that the first strategy had better performance due to its stable operating conditions. Ambühl et al. (2010) presented an explicit optimal control strategy for parallel hybrid electric powertrains. This rule-based map was used to express optimal control. Krasucki et al. (2009) proposed a

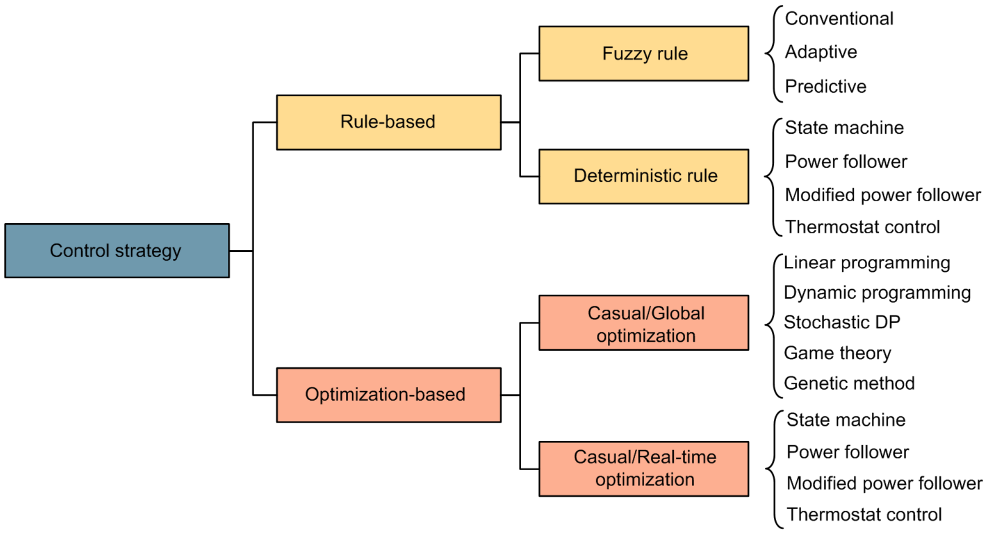

Fig. 7 Classification of control strategy for electric vehicles (DP: dynamic programming)

two-level control method for a vehicle-mounted aerial work platform. The first layer was developed using the local classic proportional-integral-derivative (PID) controllers, while the second was based on a fuzzy logic controller. Sun et al. (2011) designed a new control algorithm that combined a logic threshold method and parameter optimization technology for heavy hybrid vehicles. The results indicated that the proposed algorithm had excellent performance and fuel economy.

2.3 Energy regeneration system (ERS)

Some CMs such as electric forklifts and electric excavators are usually equipped with extremely heavy mechanical structures (i.e. the boom and fork). The machine needs to supply extra energy to ensure the heaviest mechanical structures descend at an appropriate speed. The gravitational potential energy of the heavy mechanisms (sometimes also including heavy goods) can be recovered and stored in an energy storage device, which is usually refers to a hydraulic accumulator or ultra-capacitor. In this way, the amount of wasted energy is decreased, and efficiency is improved accordingly. Note that the descending speed of mechanisms needs to be further limited to ensure the efficiency of ERS. The control strategy needs to be improved to ensure the compatibility between the ESU and ERS and the reasonable distribution of any recovered energy. In addition, the energy from the braking process of the swing system also can be reserved by the ERS. This kind of energy-saving strategy has already been used in vehicles (Itani et al., 2016). The classical two-braking control strategy for recycling brake energy is shown in Fig. 8. A problem faced by current energy recovery technology based on hydraulic accumulators is the release of the recovered energy (Tong et al., 2020c). Due to the high-power density of the accumulator and the fast energy release rate, it is usually necessary to control the energy released using a control element. Commonly used control components are control valves, bidirectional variable pumps, balance cylinders, and hydraulic transformers.

It has been shown that the recovery efficiency of ERS in CM is usually between about 20% and 60% (Lin et al., 2017b), and is determined by the system structure and type of ERS (i.e. electric ERS, hydraulic ERS, and mechanical ERS), recovery strategy, operating conditions, and size and distribution of the losing energy. In (Lin et al., 2017b), it was reported that 262 441-J gravitational potential energy can in theory be recovered from the potential energy of the boom in a 20-t hydraulic excavator. Chen et al. (2019) designed a novel potential energy regeneration system (PERS) that combines a hydraulic accumulator and valve-motor-generator for a hybrid hydraulic excavator. The simulation results show that the recovery efficiency of PERS is up to 57.96%. Zhang et al. (2013) investigated the recovery of braking energy of a fuel-cell hybrid electric bus. They found that 4.4-MJ braking energy, which takes up 13.7% of the overall energy consumed by the system, can be recovered

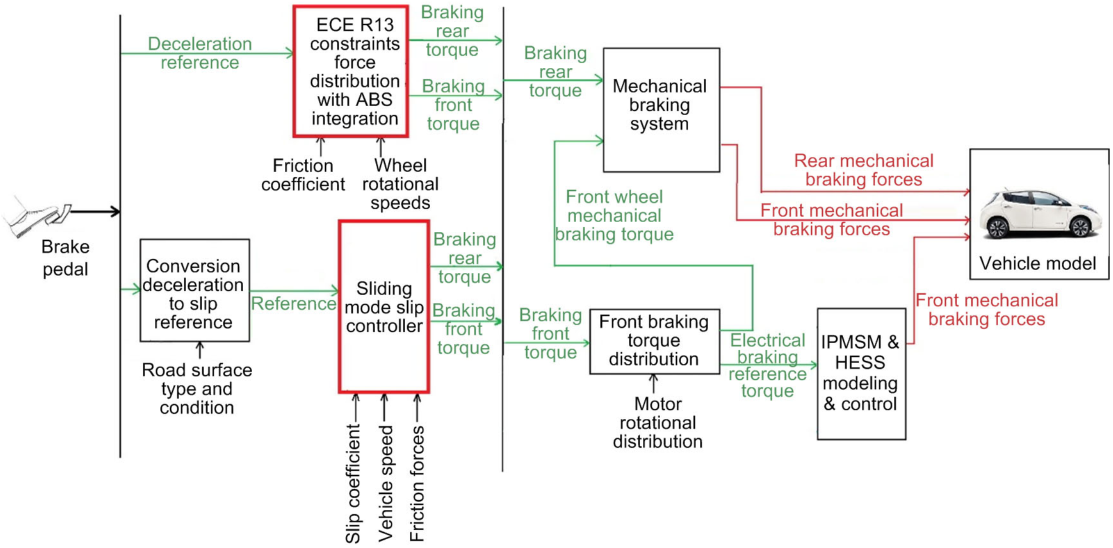

Fig. 8 Two-braking control strategy used in vehicles. Reprinted from (Itani et al., 2016), Copyright 2016, with permission from Elsevier. ECE: Economic Commission for Europe; ABS: anti-lock braking system; IPMSM: interior permanent magnet synchronous motor; HESS: hybrid energy storage system

when the bus is running on the typical driving cycle of a bus in a Chinese city.

3 Hybrid electric drive system (HEDS)

3.1 Structures and control strategy of HEDS

HEDS combines different kinds of power systems to complete the operating demand for CM with improved overall performance. Fuel consumption and exhaust gas emissions of CM can be decreased by the adoption of HEDS (Hannan et al., 2014; Tong et al., 2020a). Currently there are three mainstream types of HEDS (Enang and Bannister, 2017): series, parallel, and hybrid, as shown in Fig. 9. In the series structure HEDS, power is transmitted to the mechanical drive unit only by the electric motor, offering the advantage of both high fuel efficiency and easy operation. However, the control strategy of the series structure is difficult to develop for optimal efficiency of the entire system (He and Jiang, 2018). The parallel structure has a dynamic coupling device that integrates the power from the ICE with that from the electric motor. The electric motor is used as the auxiliary power device, and the battery pack is used as its energy storage element (Conte et al., 2014; Lü et al., 2018; Tong et al., 2020b). The effective switching of the power supply modes between the different working conditions makes the engine working in the most efficient and economical way possible. As shown in Fig. 9c, the hybrid structure is designed on the series structure and parallel structure (Wang et al., 2015), making the system a more flexible strategy.

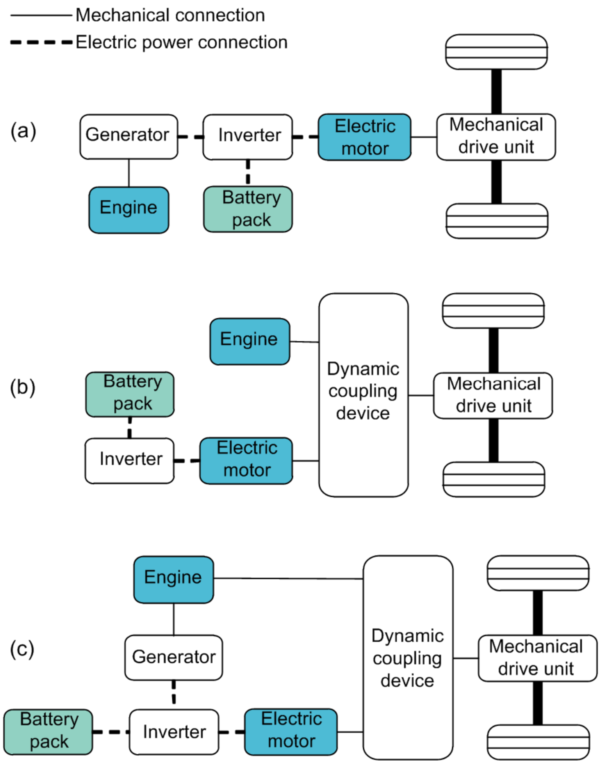

Fig. 9 Structures of mainstream hybrid power systems
(a) Series structure; (b) Parallel structure; (c) Hybrid structure

3.2 Parameter matching technology of hybrid electric construction machinery (HECM)

The basic principle of the hybrid power system is to reduce fuel consumption through the combination of electric motors and ICEs (Wang et al., 2013). The parameter matching between the different power units has a significant influence on power performance, fuel consumption, and exhaust gas emissions of CM (Xu et al., 2018). The energy flow directions in the HECM are shown in Fig. 10.

Parameter matching is one of the most critical issues in the research on HECM (Song et al., 2020). A parameter matching strategy should comprehensively consider the changes of the external load, as well as the characteristics of each component in the power system (Sun and Jing, 2010). In recent years, simulation technology has become the most efficient method for addressing parameter matching. Li et al. (2013) proposed a new parameter matching strategy for improving the performance of the hybrid power loader. The optimal parameters were discovered through the development of an objective function and a constraint function. The performance of the new strategy is demonstrated by using the MATLAB/Simulink software. Ke et al. (2020) established a state-of-charge estimation strategy of ESU for parameter matching of an electric excavator. Sun (2020) developed a comprehensive model combined with 19 components for a hybrid electric vehicle (HEV) by utilizing the advanced vehicle simulator (ADVISOR) and MATLAB/Simulink software. The critical components, including engine, electric motor, battery, and transmission, were selected according to historical experience. Parameter matching was realized by considering the power requirements of the system and then optimized by a multi-objective cellular genetic algorithm. Wang (2020) proposed a new strategy of parameter matching for an electric vehicle according to its power requirements. The ESUs of the vehicle consist of fuel cell, battery, and ultra-capacitor. Xiao (2020) optimized the system parameters of the plug-in hybrid electric vehicle (PHEV) by forward simulation. The power requirements of these systems are shown in Fig. 11.

The continuing development of hybrid CM needs to address the following key issues:

1. The optimal distribution of energy and reasonable parameter matching of the hybrid power system. In contrast to passenger vehicles, the working conditions of CM are more complicated, which makes the power output mode of hybrid power and control strategy more complicated and more demanding. Besides, the power system of HECM is more complicated compared with PECM, which makes parameter matching very difficult.

2. Reducing the cost of the hybrid system. The use of hybrid power systems on CM greatly increases the cost, which also increases the difficulty of promoting hybrid products.

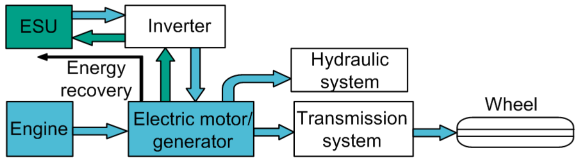

Fig. 10 Energy flow directions in the hybrid system

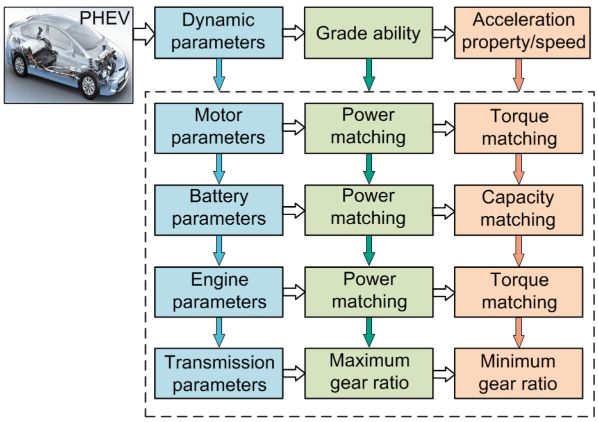

Fig. 11 Classification of system power requirements for PHEV

4 Battery management system (BMS)

The BMS used for PEDS and HEDS has the same design. For ECM, it is important to ensure a reliable energy supply. In recent years, the battery has gradually replaced other kinds of energy sources and been applied to CM, since the battery has high energy density and a long lifespan. However, the electrochemical performance of the battery will decrease as defects are generated after many charge-discharge cycles (Xiong et al., 2018). Additionally, many stress factors (e.g. temperature, depth of discharge (DOD), and charge-discharge rate) that alter the transport rate of lithium ions and the rates of electrochemical reactions will affect lifespan significantly (Hu et al., 2020). Extreme environments such as low-temperature cold storage can lead to serious consequences (e.g. the CM cannot be started or loses power when cargo is carried). Therefore, the health of the battery needs to be monitored for reliable energy supply, and timely maintenance, a favorable environment, and a reasonable charge-discharge strategy are also required to prolong the lifespan of the battery. The BMS can realize those functions and its structure is depicted in Fig. 12.

4.1 Prognostics of battery operating states

As one of the most significant functions of BMS, battery health states (e.g. remaining useful life (RUL), state of health (SOH), and state of charge (SOC)) prognostics have attracted the attention of researchers. The electrochemical performance of batteries has increased rapidly and their cost is decreasing with the appearance of new materials (Zhang WD et al., 2019; Zhang QG et al., 2020). In 2007 (Saha and Goebel, 2007), a battery would come to the end of its life within 168 cycles under a 0.75–1-C charge-discharge rate. In contrast, today the capacity of a battery only declines 4% after 1000 cycles with a 3.6-C charge-discharge rate (Severson et al., 2019). In practice, researchers usually develop an accelerated aging test to shorten test cycles as battery life is significantly affected by the operating parameters. In recent years, several kinds of algorithms, including the model-based method, data-driven method, and hybrid method, have been proposed to estimate health states. The advantages and disadvantages of popular algorithms are summarized in Table 4. Note that the computational cost of the models is being gradually reduced due to information technology continuing to evolve rapidly, such as 5G. Based on advanced information technology, BMS can estimate battery states efficiently and even download a large amount of battery data from a cloud data center to develop a more precise model; all computation can be finished within an acceptable period. In recent years, machine learning-based algorithms for prediction of battery performance have become more and more popular. The artificial neural networks such as long-short term memory (LSTM) neural network (Zhang YZ et al., 2018), feed forward neural network (Wu et al., 2016), and convolutional neural network (Ma et al., 2019) have been widely applied to predict battery operating states. These methods can accurately model battery behavior and exhibit excellent adaptability since a large amount of data is available. In addition, better prediction performance will be obtained when the artificial neural network is combined with other kinds of methods (Yang et al., 2020; Ma et al., 2021).

At present, there are still many issues for battery prognostics in CM:

1. Data acquisition. Many researchers use battery data from public datasets to develop prediction algorithms, but those are not suitable for CM applications. In addition, most battery data is collected in a laboratory environment (e.g. constant charge-discharge rate and constant temperature), which does not accurately reflect the actual application environment.

2. Generalization ability. It is important to apply the appropriate diagnostic algorithm to differing operating conditions and for various kinds of batteries. However, most research focuses on a few conditions and one or two types of batteries. In a recent work, Severson et al. (2019) developed a data-driven estimation method based on a comprehensive dataset that

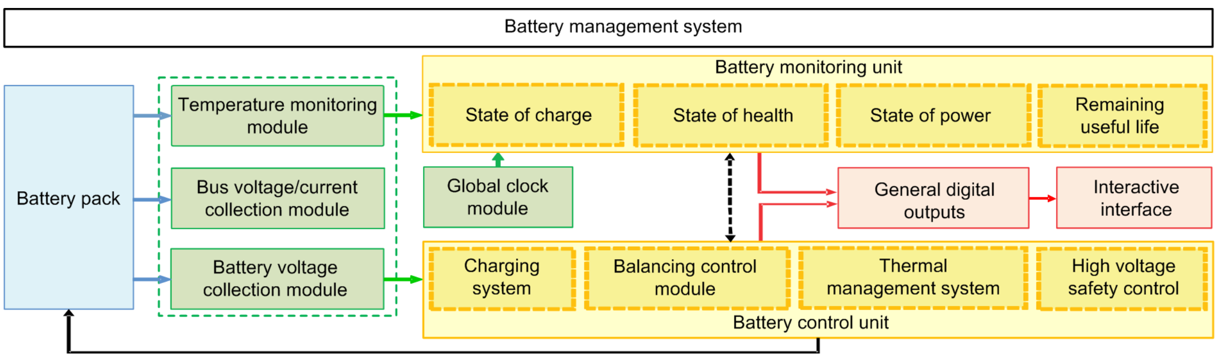

Fig. 12 Structure and functions of a typical BMS

Table 4 Advantages and disadvantages of popular algorithms for battery state prediction

Algorithm		Advantage	Disadvantage
Model-based	Mechanistic (Ning et al., 2006)	(1) Based on internal electrochemical reactions; (2) High precision and good generalization ability	(1) Requires technical knowledge; (2) Hard to identify the proper model parameters; (3) High computational costs
	Equivalent circuit (Saha et al., 2009)	The degradation mechanism is considered	(1) Requires technical knowledge; (2) Electrochemical impedance spectrum can affect lifespan of battery
	Empirical (Bloom et al., 2001)	(1) Simple to develop; (2) Wide application	(1) Low generalization ability; (2) Requires updates to model parameters
	Fused (Guha and Patra, 2018)	(1) Extracts more information; (2) Applicable to early estimation	(1) Introduces more error sources; (2) More complex failure criterion
Data-driven	Naive Bayes (Ng et al., 2014)	(1) Simple to establish; (2) Good tolerance for missing data	Adopts attribute independence assumption which is often invalid
	Support vector machine (Nuhic et al., 2013)	Performs well in nonlinear, small sample data problems	(1) Lack of sparseness; (2) Limited by Mercer theorem when selecting the kernel function
	Relevance vector machine (Liu et al., 2015)	(1) Good sparseness; (2) Can solve overfitting or underfitting; (3) No limitation of Mercer theorem	(1) Poor computational efficiency for large sample data; (2) Inapplicable to long-period estimation
	Gaussian process regression (Liu et al., 2013)	Performs well in small size and high-dimension data	(1) Poor computational efficiency for large data; (2) Lack of sparseness
	Artificial neural network (Zhang YZ et al., 2018)	(1) Excellent learning ability and traceability for nonlinear data; (2) Integrates various kinds of information	(1) Based on sufficient training data; (2) Difficult to balance performance and computational costs
	Wiener process (Zhang ZX et al., 2018)	(1) Performs well in the non-monotonic process problem; (2) Distribution of the first hitting time can be formulated	(1) Poor performance for heterogeneous and nonlinear data; (2) Based on the property of Markov
	Entropy analysis (Hu et al., 2016)	(1) Easy to implement online estimation; (2) Effective features extraction	Requires sufficient and high-quality data
Hybrid	(Dong et al., 2014)	(1) Requires less data compared with data-driven methods; (2) More flexible compared with model-based methods	(1) Increases the complexity of the model; (2) Introduces more error sources

included 124 commercial lithium-ion batteries. The batteries were operated at different charge-discharge rates, and their lifespans ranged from 150 to 2300 cycles.

3. Evaluation criterion. The performance indicators of algorithms can be classified as accuracy, robustness, generalization ability, and computational costs (including time costs and hardware requirements). For precision evaluation, indicators such as mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) are widely utilized. For other performance indicators, however, there are no available quantitative criteria to evaluate prediction algorithms. Therefore, it is difficult to identify the comprehensive properties of the model.

4.2 Thermal management system (TMS)

An appropriate environment can be established by the TMS to maintain the highest performance of batteries no matter where the CM is operated. In contrast to automobiles, CM is more likely to be used in high-temperature or extremely cold environments. Batteries will be especially affected by abnormal temperatures without the TMS. The TMS can be divided into four categories, i.e. the air-based method, liquid-based method, material-based method, and fusion method, and a TMS also can be passive or active (Rao and Wang, 2011). The schemes for air-based and liquid-based methods are shown in Fig. 13. The material-based method uses the characteristics of phase change materials (PCMs), which

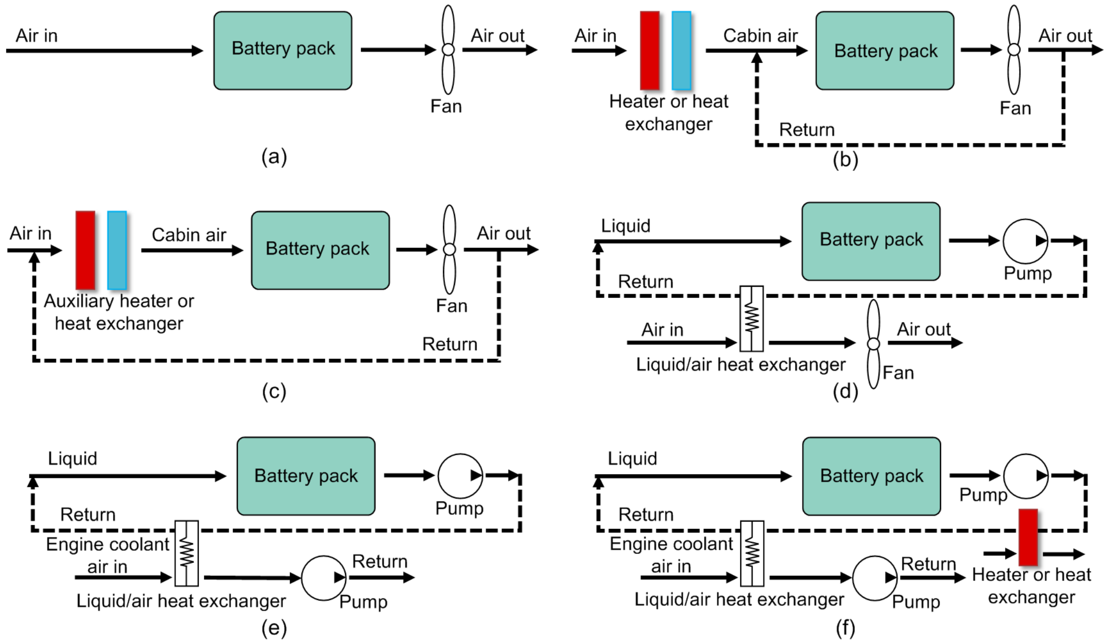

Fig. 13 Schemes for air-based and liquid-based TMSs

(a) Passive air cooling; (b) Passive air cooling or heating; (c) Active air cooling or heating; (d) Passive liquid cooling; (e) Active moderate cooling or heating; (f) Active cooling at a high temperature or heating at a cold temperature

have high conductivity for high temperature and low conductivity for low temperature. Therefore, the PCM can be used for either dissipating heat or preserving the heat of the battery pack.

The scheme for the TMS will be affected by many factors such as the type of battery (cylindric, prismatic, elliptic) and the structure of CM (Al-Hallaj and Selman, 2002). The TMS used in a five-chair electric vehicle is depicted in Fig. 14. The system utilizes a heat pump to develop a cooling and heating loop. Zolot et al. (2002) developed a parallel airflow TMS for cooling the battery pack in a hybrid vehicle. Wang et al. (2014) investigated the influence of cell distribution and fan locations. The results showed that the best cooling performance was realized when the fan was located on top of the batteries.

5 Environmental benefits of ECM in China

According to the U.S. Energy Information Administration (EIA, 2017), the construction industry is responsible for 11% of energy-related carbon emissions globally. Most CMs are diesel-powered, and emit significantly more pollutants than those from automobiles, including particulate matter (PM), nitrogen oxides (NO_x), and hydrocarbons (HC). To accomplish reductions in emissions, China has been continuously enacting stricter emission standards for non-road CM since they were first issued in 2007. The new China IV emission standard for non-road CMs will be officially implemented in 2022. Furthermore, as many countries have policies for banning the sale of fossil-fuel powered vehicles in the future, it is also likely that countries will be planning to ban the sale of CM with conventional fuel at some point. As such, electrification of CM has already become an inevitable technological trend because of its massive environmental benefits. To provide reference for government and CM manufacturers, the CM emissions in China (2016–2020 and 2030) are roughly estimated here based on the emission factors of each pollutant (PM, NO_x, HC) and annual fuel consumptions. We employed average non-road CM emission factors to estimate annual emissions according to the non-road emission inventory guidelines released by the Ministry of Ecology and Environment of the People's Republic of China (MEE) (MEE, 2019). The fuel consumption rate was obtained based on the testing data of different types of CMs under typical operating modes (Hu et al., 2019). The estimated national total emissions of each pollutant are shown in Fig. 15. In

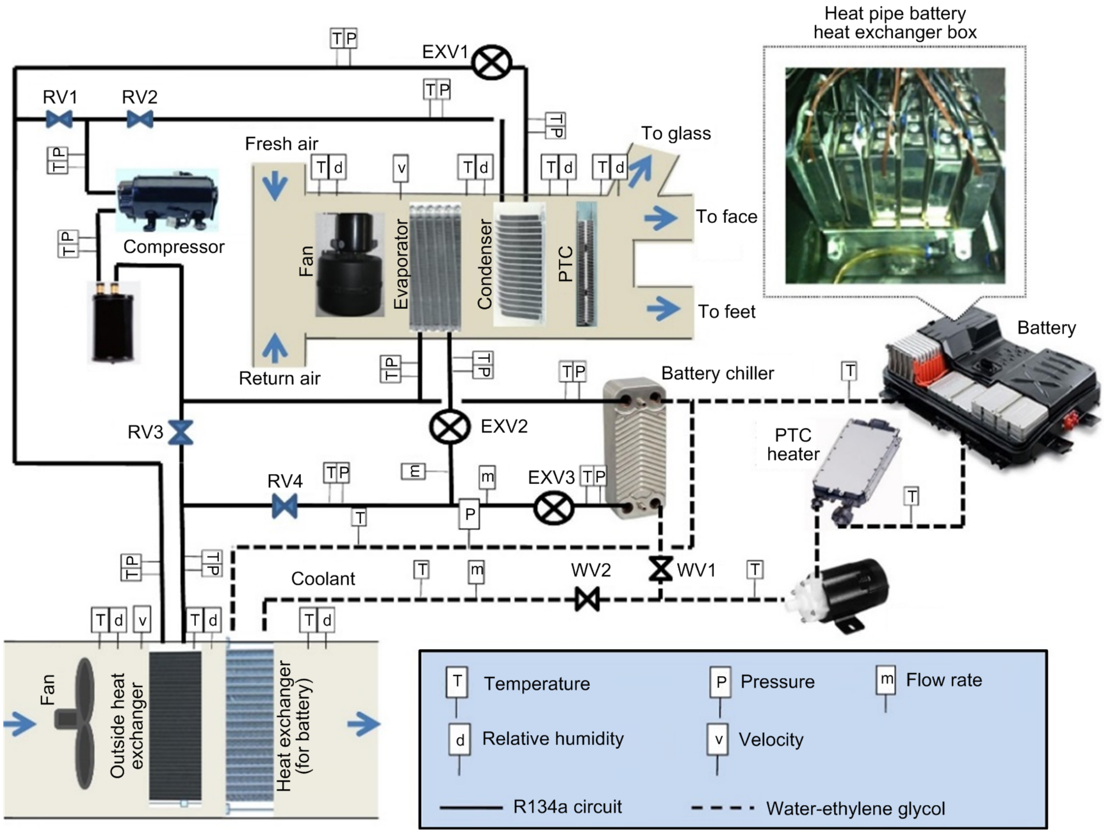

Fig. 14 Structure of the TMS used in an electric vehicle. Reprinted from (Zou et al., 2016), Copyright 2016, with permission from Elsevier. PTC: positive temperature coefficient; EXV: expansion valve; RV: refrigerant valve

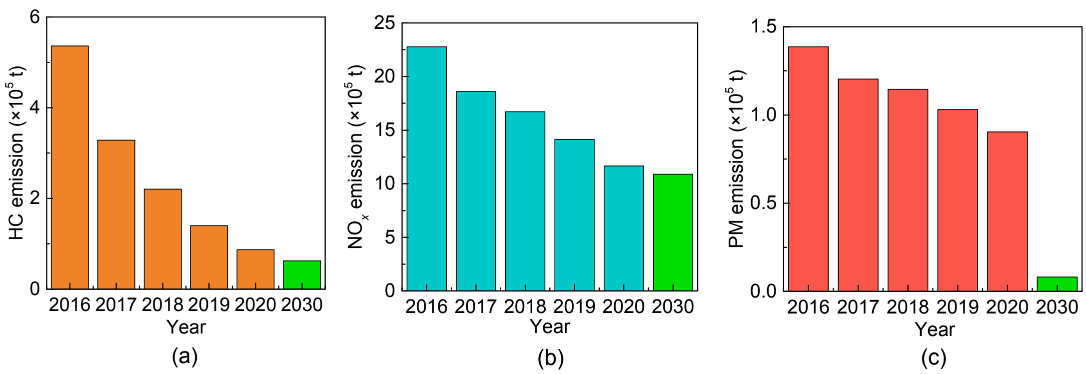

Fig. 15 Estimated national total CM emissions in China (2016-2020 and 2030)
(a) HC; (b) NO_x; (c) PM

comparison with the emission data released in the China vehicle environmental management annual report by MEE, our predictions are in decent agreement with differences less than 20%. For example, in 2019, the national total emissions for HC, NO_x, and PM were 140 169 t, 1 412 525 t, and 90 458 t, respectively. Considerable decreases in all three pollutants are observed from 2016 to 2020 due to the implementation of exhaust after-treatment technologies such as diesel oxidation catalysts (DOCs), diesel particulate filters (DPFs), and selective catalytic reduction (SCR) catalysts. Additionally, we have predicted the total emission in 2030 based on the assumption that all existing CMs comply with non-road

China IV standard and 20% of in-use CMs in China will be electric with zero emission. The national total emissions for HC, NO_x, and PM in 2030 are forecast to be 62 700 t, 1 089 000 t, and 8250 t, respectively (Fig. 15). Although the number of in-use CMs is assumed to grow steadily from 2020 to 2030, the predicted total emissions for all pollutants will still be less than the level of 2020 especially for PM, due to the replacement of pre-China IV CMs with China IV CMs equipped with more advanced after-treatment technologies as well as with a significant number of ECMs. In short, we have shown that the implementation of ECM in China shows considerable environmental benefits, and more government incentives are encouraged to further motivate CM manufacturers in developing more ECM models for the Chinese market.

6 Conclusions

Traditional CM no longer satisfies the demand for energy saving and environmental protection. The development of ECM that utilizes clean and renewable energy is of great importance in the CM industry. In this review, key technologies of PEDS and HEDS were discussed for the design of ECM. Due to harsh operation conditions, ECMs, such as the mining truck and excavator, demand high battery performance with long cycle life, fast charging speed, and stable current output. As the electrochemical performance of batteries continues to improve, BMS design for ECM becomes more and more prominent and therefore we have included a deep discussion on existing BMS technologies. In addition, we roughly estimated the national total CM emissions from 2016 to 2020 and the potential environmental benefits of employing ECMs by 2030.

With increasing regulations on emission control and the promotion of clean energy, the market of ECMs in China has been rapidly expanding. Top CM players such as SANY and LiuGong have already made a significant effort in the progress of electrification through several strategic collaborations with Contemporary Amperex Technology Co., Limited (CATL), a leading battery manufacturer in China. In addition, the rapid development of information technology, e.g. artificial intelligence, internet of things, and 5G is transforming the CM industry. Many new ECM models are already equipped with online data transmission features. To improve operation safety and efficiency, companies such as XCMG and Hangcha are developing technologies to achieve autonomous driving and real-time communications with road infrastructure and warehouses.

Contributors

Zhe-ming TONG and Jia-zhi MIAO designed the research and wrote the first draft of the manuscript. Yuan-song LI and Shui-guang TONG conducted the literature review. Qian ZHANG and Gui-rong TAN processed the data. Shui-guang TONG revised the final version and provided the funding support.

Conflict of interest

Zhe-ming TONG, Jia-zhi MIAO, Yuan-song LI, Shui-guang TONG, Qian ZHANG, and Gui-rong TAN declare that they have no conflict of interest.

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