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Development and key technologies of pure electric construction machinery

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ABSTRACT

With global warming and the energy crisis becoming more serious, the emission regulations for construction machinery (CM) are increasingly strict. The pure electric drive system is an inevitable trend for CMs. Although the pure electric drive system is widely used in the industry field and some technologies have been successfully transplanted to the mobile machines, it's not easy for CMs to realize the electrification. Types of pure electric CM (PECM) are discussed firstly to give a glance at PECM. Then the characteristics of a pure electric system for CMs are introduced. Key technologies, like variable speed control of the electric motor (EM), hydroelectric EM driving, new hydroelectric actuator, power supply, and energy recovery, are analyzed in depth. The difficulties of CMs to realize the electrification by comparing the difference between the pure electric power used in CM and the pure electric power used in the other fields. Moreover, the researches and developments in the pure electric drive systems for CMs are introduced. Finally, the challenges that researchers and the CM manufacturers will face are forecasted.

1. Introduction

As concerns the global warming, energy crisis, rise in oil prices and tightened regulations on exhaust gas, the requirements for energy conservation and pollution reduction of construction machinery (CM) are increasingly strict. Without sacrificing the working performance, controllability, security, and reliability, CMs have been still working with high fuel consumption and high pollution because of the load fluctuation. New technologies are hoped to solve this problem. To meet this challenge, the electric drive technology has already been applied to automobiles including electric hybrid concept [1-3] and pure electric concept [4–6]. And the electric drive technology is also increasingly being spread and applied to the CMs [7-10].

The electric hybrid technology is a method of using two power sources of the engine and the electric motor (EM). It is an environment-friendly and high-efficiency technology that enables energy efficiency and reduction of exhaust gas through optimum power distribution. And it can be divided into series type, parallel type, and power-split type that is a combination of serial and parallel types. Hybrid technology solved the impact of load fluctuation on the engine efficiency and energy efficiency has been improved up to 10–30% [7]. However, the hybrid system significantly adds the complexity to the power train by increasing methods for power flow and adding the complicated control for energy management. Furthermore, some hybrid systems still exit noise and vibration. The engine is still the main power source, it still depends on oil and produces emissions. The pure electric drive system which adopts EMs to substitute the engine to drive the hydraulic pump or directly drive actuators can realize real zero-emission and improve the energy efficiency [11], and it paved the way for the intelligent development of CM [12].

The PECMs address the issue of emissions. However, when the pure electric drive system is applied to CMs, the driving line, control strategy, hydraulic control and other aspects of CMs had been changed. This paper will discuss the following issues. The types, characteristics, key technologies of PECM are analyzed in the first three sections. Then, the difference between a hybrid car and hybrid construction machinery will be discussed in Section 4. Moreover, the research and development of pure electric earthmoving equipment in universities and manufacturers are introduced in Section 5 and Section 6. Then, the challenges of the PECMs are presented in Section 7. Conclusions are summarized in Section 8.

1.1. Type of PECM

Since the electric drive system of PECM is only composed of EM and electric power supply, it is a pollution-free CM with no emissions of carbon dioxide. Compared to an engine drive CM, it has the advantage of low noise and low maintenance costs. However, its working

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Table 1
Parameters contrast of commonly used ESUs.

Items	Lead-acid battery	Flywheel	Supercapacitor	HA	NI-MH battery	Lithium battery
Specific power (W/kg)	75–300	400–1500	500–5000	2000–19,000	150–200	250–340
Specific energy (Wh/kg)	30–50	10–30	2.5–5.5	2	100–120	75–200
Energy density (Wh/L)	50–80	20–80	35	5	150–180	200–500
Cycle times	500–1500	20,000	100,000	100,000	2500	2000–10,000
Efficiency	<80%	≤96%	≤95%	90%	90%	≤95%

Table 2
Analysis of advantages and disadvantages of the EMs.

Types	Advantages	Disadvantages
DC motor	Low cost, easy control, good speed regulation performance	Large volume, frequent maintenance
PMSM	High efficiency, simply structure, small volume, light weight	High cost, magnetic decay at high temperature
Asynchronous motor	Simple structure, good reliability, low cost, easy control	Low efficiency, bad speed regulation performance
SRM	Simple structure, good reliability, low cost, easy maintenance	Big torque fluctuation, loud noise

performance depends on its power supply unit including the AC power grid and the electric energy accumulator. According to the power supply, the PECMs can be divided into four types.

1.1.1. Power grid type

The power grid is adopted to supply power directly and the working time is not limited. This kind can save battery costs, but the working scope is limited, which is suitable for those where there is easy access to the power grid. In addition, because of the limitation of the cable of the power grid, working flexibility is greatly reduced. Moreover, the swing mechanism of the hydraulic excavator (HE) needs to rotate more than 360°, and the power supply device needs special design, to ensure that the cable will not affect the rotary motion of the HE. This type is suitable for the places where it is easy access to power grid, such as mine, tunnel and so on.

1.1.2. External power type

The arrangement of this type is similar to that of the power grid power supply type. The power grid is substituted by the battery that is arranged in a separate device called a mobile power supply truck (MPST). It especially suits the blind area of the power grid. MPST can solve the problem that the battery of the crawler PECM is hard to be charged. The working time can be improved and the cost can be reduced through increasing the battery capacity. However, MPST is pulled during the operation that restrains the walking condition of the CM. This type is more suitable for the rental mode of MPST or the emergency reserve.

1.1.3. Battery type

In this type, the battery is the only energy storage unit (ESU) to supply DC power to PECMs. Nowadays, the electrochemical battery is more suitable for storing electric energy for CMs. They are arranged on the whole machine. The capacity of the battery determines the operating time and cost of the CM. At the same time, the battery needs to be recharged regularly. Therefore, it is suitable for wheel CMs, such as wheel excavator, wheel loader and forklift, etc. However, the heart of the matter is to arrange enough room for energy storage units for PECMs. This type is suitable for the places where the power grid is not convenient or the machines need to walking around frequently, such as the port, warehouse and so on.

1.1.4. Battery and power grid type

This type of PECM can be powered by the power grid or the battery. Because the power grid can be adopted as an independent energy supply, the size of the battery can be reduced considerably. The capacity of the battery can be selected according to the actual requirement of the user. It is suitable for the crawler PECMs, such as crawler excavator. Due to the combination of the battery and power grid, this type almost suitable for all working conditions.

According to the requirement, there may be other combinations, such as power grid type and external power type. In this type, they can use the same joint to the power supply.

2. Characteristics of the PECM

The core components of the power unit of the pure electric drive system are ESU and EM. Based on the working characteristics and operation mode of CM, higher requirements are made for them. To ensure the minimum operating time of the machinery and the dynamic performance of continuous large current discharge in case of sudden large load, the ESU is required to have a higher energy density and power density. To meet the requirements of a wide range of flow matching and quick response of the system, the EM is required to have high power density, speed regulation efficiency, strong overload capacity, large starting torque and fast torque response.

2.1. Energy storage unit (ESU)

ESU is the key component of a PECM. At present, there are many ESUs applied in the market, such as a flywheel, lead-acid battery, nickel-metal hydride (NI-MH) battery, lithium battery, supercapacitor and hydraulic accumulator (HA). A comprehensive evaluation of various energy storage is provided in Table 1. It can be seen that the lithium battery has the highest energy density, power density and cycle life [13]. While HA has the merits of high-power density, long cycle life, and low cost. It can be used as an auxiliary energy to reduce the performance requirement of the main energy storage [14,15]. Compared with vehicles, the working conditions of CM are complicated and the load fluctuates violently. The pure electric drive system should not only ensure it can operate for about 8 h on a full charge, but also ensure the explosive force during the heavy load excavation conditions. Furthermore, the ESU often experiences deep charge and discharge, which puts forward higher requirements on the cycle times of the ESU. Therefore, the energy form of a single ESU used in PECMs is not the most ideal ESU for CM.

Considering most of the CMs being driven by a hydraulic system, it is meaningful to combine the lithium battery that has a high energy density and HA that has a high-power density into a hybrid type for the electric drive system. The battery ESU guarantees the working time, and the hydraulic ESU ensures dynamic performance.

2.2. Electric motor (EM)

Nowadays, types of EM commonly used are DC motor, permanent magnet synchronous motor (PMSM), switched reluctance motor (SRM) and asynchronous motor. Table 2 shows the advantages and disadvantages of the four types of power EMs. Among them, DC motor is not suitable for PECMs because of its complicated mechanical structure and frequent maintenance. The SRM attracts an interest in PECMs because it has no rare-earth materials and has the advantages of simple structure, low cost, high efficiency, and reliability. However, compared with traditional drives of speed regulation, SRMs, because of its characteristics, are easily affected by torque ripple and radial distortion that lead to noise and vibration [16]. To solve the noise and vibration is an important and urgent issue for the optimization of the SRM for high-performance PECMs. This kind of EM is expected to be widely used in PECMs after the technical upgrades.

By now, asynchronous motor and PMSM are mostly used in PECMs. The biggest advantage of PMSM is its high power density and torque density [17,18], which is especially important for those CMs with limited installation space. Compared with PMSM, the biggest advantage of asynchronous motor is low cost, reliable operation, convenient maintenance, and can withstand a large range of operating temperature changes. In addition, although the asynchronous motor has disadvantages in weight and volume, this disadvantage can be compensated by the reasonable design of counterweight. As a result, the asynchronous motor can be used in large-tonnage class PECMs.

2.3. Characteristics analysis

Combined with the development of battery technology and EM drive technology, the characteristics of the pure electric drive system suitable for PECMs are as follows.

2.3.1. Pure electric drive systems applied in wheel CM and crawler CM have different characteristics

For crawler CM, such as crawler HE, its mobility performance is bad. While the walking mechanism and the operating mechanism hardly work at the same time. Commonly, the walking mechanism adopts two sets of hydraulic motors for the left and right tracks. The electrification of the crawler CMs is focused on the operating mechanism. The reason is that the cost of replacing a hydraulic motor with an EM is high and the effect of energy-saving is not significant.

For wheel CM, such as wheel loader, wheel HE and so on, the walking system and operating system are both the basic working conditions under normal operating mode. Therefore, electrification of wheel CMs needs to be carried out on both the operating system and the walking system. However, most wheel loaders generally adopt a torque converter that has low efficiency and usually results in a poor fuel economy. If the EM is used to substitute the engine to drive the torque converter, energy-saving and working performance of the whole machinery cannot be improved to an ideal level. Therefore, it is necessary to design a new power transmission to substitute the torque converter to enhance the efficiency of the whole machine. Because the working mode of wheel loaders is complicated and variable, it needs to switch frequently during work.

2.3.2. Pure electric drive systems applied in different tons CMs have different characteristics

Take the HEs for example, HEs are divided into four levels, miniature (<4 tons), small (4–10 tons), medium (10–40 tons) and large (>40 tons), according to the weight of the whole machine. Nowadays, the maximum power of the mature pure electric drive system for PECMs is under 500 kW and the rated capacity of the battery is approximately 800 kWh. Hence, large tonnage PECMs can be only supplied by the power grid. The less the tonnage of the PECMs, the more suitable for the battery type. However, the biggest difficulty for miniature CMs electrification is to find the installation space for the batteries. For medium CMs, the installation space is enough, so the asynchronous motor with a lower cost can be used. But because the power of the powertrain unit and the capacity of the ESU are larger, the cost is higher. Taken together, the electrification of small tonnage HE is more suitable for battery type while that of the large tonnage HE and miniature type HE is more suitable for power grid type considering today's technologies.

2.3.3. Multi-EM drive is superior to the single EM drive

In an automobile, only one actuator drives the wheels. However, for a CM, there is more than one actuator. According to its working mode, sometimes there are several actuators work at the same time to share power, and sometimes there are only one actuator works with full power. The load of the CM fluctuates violently and the average power is only about 30% of the peak power. To dynamically match the flow rate between the hydraulic pump output and the load required, the EM needs to accelerate/decelerate frequently in a standard working cycle that is approximately 15–20 s. For a single EM, the working point distribution in a large area, it is relatively harsh that over 85% of the total working area is the highly efficient area. Hence, it is not an ideal choice to use only a single EM to simulate the engine function. Then a scheme using a multi-motor electric drive instead of a single-motor electric drive in a PECM is proposed. The multi-motor is coupled by a power coupling mechanism. The novelty of this scheme is that the adoption of a multi-EM drive can reduce the energy losses when the PECM works at a constant speed with the fluctuating torque.

2.3.4. Combination of HA and lithium battery is more suitable than a lithium battery for PECMs

The ESU includes kinds of batteries, supercapacitor, and HA. They have different characteristics in energy density, power density, lifetime, etc. Considering the maximum operating time required for a fully charged ESU for PECMs, the energy-type power lithium battery is generally adopted as the ESU. However, the working conditions of CM are relatively complicated such as crushing hammer mode, strong excavation, etc. On many occasions, EM works in high torque mode with near zero speed. Under this circumstance, if the batteries are still used for power supply, the energy consumption will be large and the efficiency will be low. While the hydraulic motor with a HA can work efficiently in high torque mode with near zero speed.

Hence, existing ESUs have several challenges when applied to PECMs. Using a single form of ESU is difficult to meet the different demands of PECM before a technological innovation comes. Therefore, designing an integration of an energy storage system for various types of PECMs is the expected development in the future.

3. Key technologies of the pure electric drive system applied to PECMs

3.1. Variable speed control strategy

After substituting the EM for the engine, compared with the engine speed regulation performance, the EM is superior in dynamic response, speed control accuracy, overload capacity, and others. Most of the current PECMs use the EM to simulate the engine function, while the EM advantages do not be shown out in PECMs.

Compared with automobiles, the control features of the PECM are multi-objective optimization control. The control object is not only the EM, but also the control elements of the hydraulic system. It includes global flow rate optimization control, variable constant power control, automatic idle speed control [19], global power matching between EM, hydraulic pump and load, etc.

As the state quantity (pressure) of the hydraulic system is easy to detect, then how to dynamically control the EM according to the state signal feeding back from the hydraulic system and to make the efficiency and performance of the CM at the optimum state are a larger challenge. During the working period, the HE's pump outlet pressure is easy to measure. Iterative learning control and fuzzy control strategy of the cloud model suitable for HE are put forward, which using the pump outlet pressure, load sensitive signals and the feedback pilot pressure as the feedback signals for the EM controller. The realization of torque prediction and direct torque control [20] of the power system is a key technology for CM electrification.

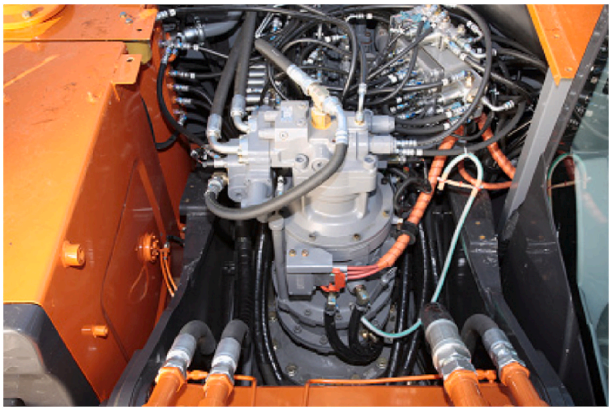


Fig. 1. The swing device of the ZH200 hybrid HE [37].

3.2. Novel hydraulic control technology based on electric drive

After the adoption of the electric ESU, the hydro-mechatronics advantages can be fully utilized to further improve the PECM efficiency [21] These technologies include the motor/generator-pump/motor (M/G - P/M) closed hydraulic system, new servo EM-hydraulic pump combination [22–24], the cylinder driven directly by EM, electro-hydraulic actuators [25,26] and hydraulic transformers [27–29] using new EM variable speed control, etc.

3.3. Energy regeneration system (ERS) of the boom

For large level CMs, usually, its boom has a heavier weight than that of the load. When the boom descending, it needs extra energy to keep the boom from going down too fast instead of supplying oil to make the boom downwards. During boom descending, the boom gravitational potential energy is consumed on the orifice of the multiway valve and dissipated in the form of heat energy. Therefore, it can further increase the energy-saving in PECMs by the boom ERS. Because the CM boom is heavier, it can reduce the energy consumption if the potential energy can be reserved using the ERUs, such as electric type or hydraulic type, when the boom descending and the stored energy can be reused when there are needed. Moreover, the control performance of ERS should be guaranteed because it can promote energy utilization effectively. To make the driver obtain the same control performance, the control of the ERS should ensure that the boom descends with the same velocity as that in the conventional CMs. Therefore, the CM with ERS should have a similar movement to that of the traditional CM [30-35].

3.4. ERS of the swing system

For pure electric hydraulic excavators (PEHEs), the efficiency can further be improved if the kinetic energy of the swing of the upper mechanism braking process can be recovered. When s PEHE is adapted to carry and dump the materials in mines and other sites, the upper mechanism rotates frequently that leads to short acceleration and deceleration time of the swing system. If an EM is adopted to substitute the hydraulic motor to drive the swing system, the requirements for the EM speed regulation system should be quick enough to respond the speed signal and the EM has no torque jerk and speed overshoot to make the operator feel comfortable. And during the fine operating conditions, the swing and the arm are working at the same time. The swing torque of the upper mechanism is to ensure that the bucket is reliably pressed against the wall [36]. In traditional HEs, swing torque is regulated by the spool displacement of the multiway valve, while that in PEHE is guaranteed by the EM. In other words, the EM works in a bad condition that the speed is nearly zero but the torque is vast.

Hence, it is worthy of research to keep similar operability as that of the hydraulic motor. In PEHEs, the compound driving device, which includes a hydraulic motor and an EM, is suitable to the swing system for the PEHEs. The swing EM is located between the swing device's hydraulic motor and the swing reduction gear (seen in Fig. 1). The swing electric motor is a water-cooled PMSM, and its torque is controlled by commands from the EM controller (EMC). This includes producing regenerative electric power when the rotation of the HE upper structure is decelerating and assisting the swing hydraulic motor when the rotation of the HE upper structure is acceleration. This system can integrate the advantages of hydraulic control and electrical control.

3.5. Auxiliary drive control technology of the PECM

After the engine is removed, the original air conditioning compressor, a brake air pump that is used for wheel CMs, and radiator drive unit need to be driven separately. In addition, considering that the EM characteristics when driving the main hydraulic pump and the pilot hydraulic pump are different, the PECM can drive them separately. Also, the air conditioning compressor, radiator, pilot pump, and other accessories need to be driven. The power consumed by the accessories accounts for 10–20% of the total power. Moreover, it is not a simple start-stop logic control between accessories. It is also necessary to optimize and coordinate different accessories according to the CM working condition.

4. Differences between the pure electric power used in CM and the pure electric power used in the other fields

4.1. Differences between the industrial EM and the EM used in the PECM

Industrial EMs typically are powered directly from the power grid, while PECMs utilize the batteries. Moreover, the CM working conditions are complicated. Therefore, compared with the industrial EM control system, the electrical driving system of PECM has higher requirements on the EM, electricity safety and control system.

(1) Good acceleration performance. To dynamically match the flow rate between the pump and load, the EM of PECM needs to accelerate/decelerate frequently during a standard working cycle (15–20 s).
(2) Wider speed range. To give a full play of the EM advantages and simplify the hydraulic system, the quantitative pump can be used to substitute the original variable pump when the PECM adopts the speed regulating EM. The EM must have a wider speed range that is determined by the working speed range of the hydraulic pump, which is from 400–3000 rpm.
(3) Strong overload capacity. The CM load power has the characteristics of large peak power and low average power. Since the average load power of most CMs is only between 1/3–3/5 of the peak power, the EM used in the PEHE is expected to have a strong overload capacity.
(4) High efficiency. To prolong the working time and reduce the installation capacity of the battery after a full charge, the EM is required to have high efficiency.
(5) PECM usually works outdoors. The requirements for safety, reliability and protection level of the EM are even higher.

4.2. Differences between the pure EVs and the PECM

In recent years, pure EVs have got a rapid development [38]. However, compared with vehicles, pure electric drive systems applied in CMs have the following important differences.

4.2.1. Working style

Take HE an example, HE is a kind of multi-purpose CM, which can be used in excavating, leveling, loading, crushing and other working

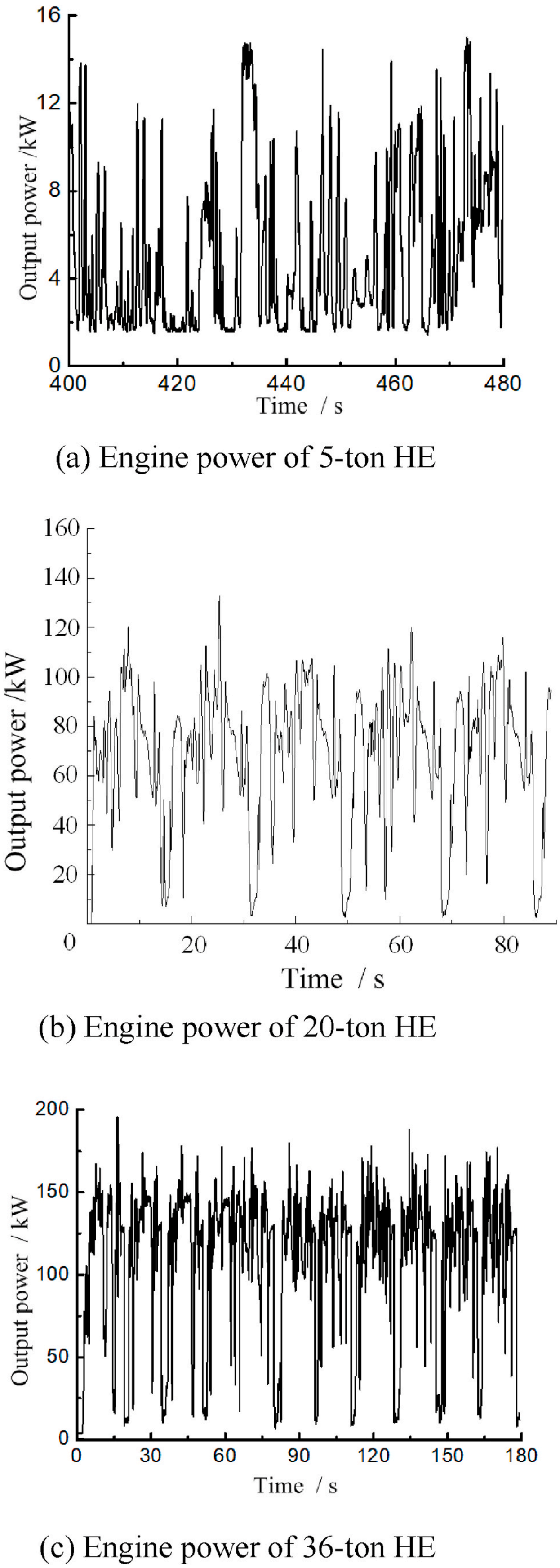


Fig. 2. Engine power of different tons HE.

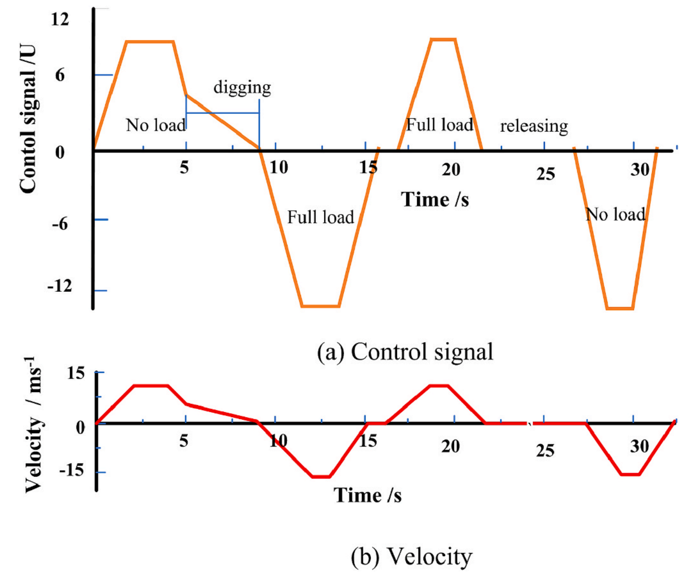


Fig. 3. Control signal and velocity of 5-ton wheel loader.

modes. The HEs working conditions are also relatively complex and can be generally divided into the heavy load, medium load, and light load. The HE usually performs the same action repeatedly during work, and the output power of the power source fluctuates violently and periodically that is usually 15–20 s (seen in Fig. 2). Taking a 20-ton HE as an example, the output power of the power source varies dramatically between 10–120 kW in about 16 s. As a result, the operating conditions and environment of a PECM are more complicated and the power density is higher, so the requirements of the main components for dynamic response and the impulse overload capacity are higher. While the EV working condition is more stable, mainly including starting, accelerating, uniform speed, braking, uphill, and downhill. In most stable driving processes, the load is stable and the power source needs not to change with the change of the load all the time. A certain control strategy can be used to make the EM run stably in the ideal region. However, during the CM working process, the load changes all the time, and the EM needs to adjust to match the load change.

4.2.2. EM

The EM used in pure EV is mainly to play the characteristics of low speed and high torque to realize the rapid acceleration when the vehicle is started. While the EV is running at high speed, the EM speed is large, but the output torque is small. That is to say, the EM adopts weak magnetic control in the high-speed area to expand the working range of the EM [39] [.] Wheel CM is similar to the pure EV. But because the EM needs to drive both the walking mechanism and the hydraulic pump through the power coupling box simultaneously, and limited by the speed range of the hydraulic pump, the EM speed change of cannot completely depend on the walking speed demand. In addition, because some wheel CM, such as a heavy forklift, has a large load, the power demand of the power EM differs by more than 7 times under the two working conditions of no-load on a flat road and full-load uphill. And also, take the wheel loader as an example, it is illustrated clearly from the control signal and velocity of 5 tons wheel loader shown in Fig. 3. There is approximately 2–3 s for the boom to regenerate the potential energy within a 30 s working period. And the velocity changes rapidly and periodically. There is one condition that must be considered. When wheel loader works in digging mode, the digging force is great while the velocity is very low. That is to say, the EM should output peak torque at a fairly low speed. In the original wheel loader, a torque converter is applied to adapt to such conditions. However, if the torque converter is cancelled, the peak power is four times the rated power. Thus, the

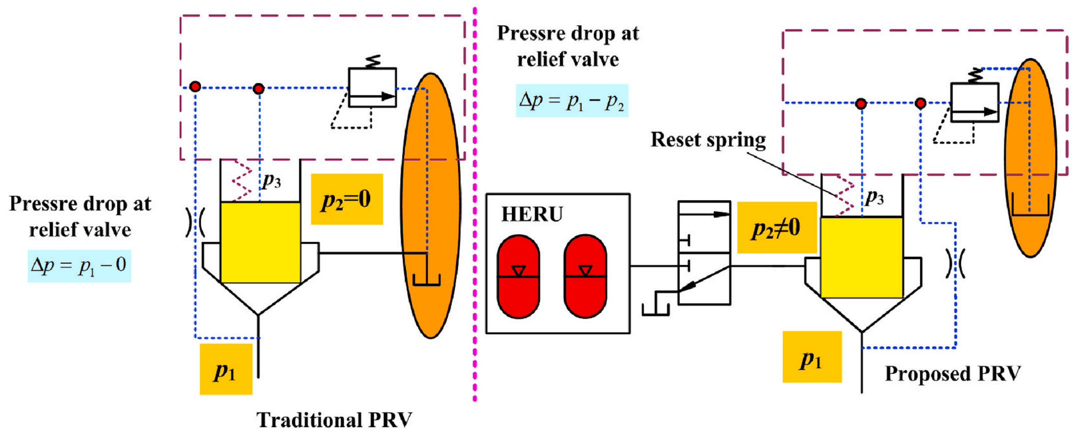


Fig. 4. Comparison of the structure principle of PRV with and without HERU.

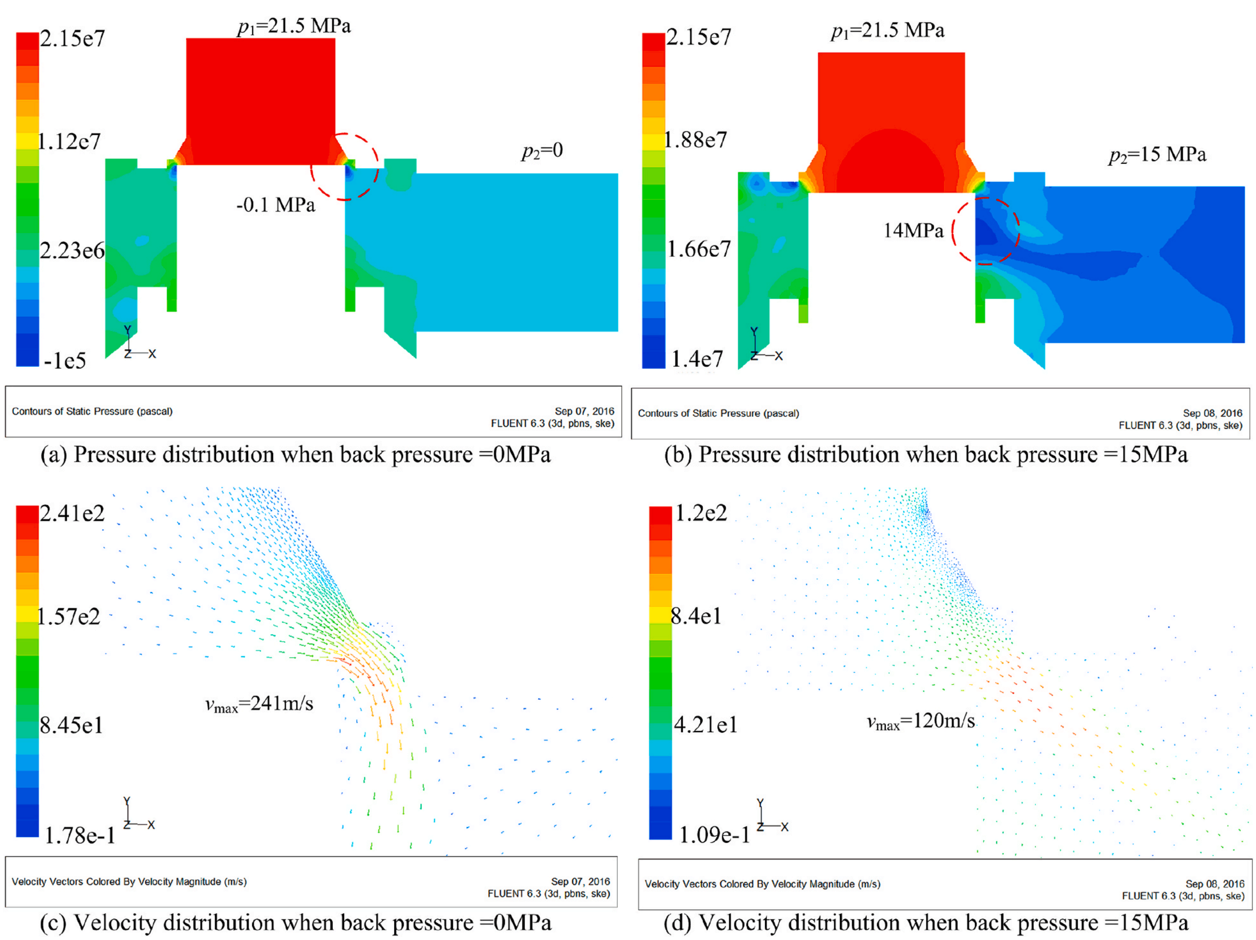


Fig. 5. Comparisons of the distribution of the pressure and velocity of PRV with and without HERU.

requirements for the EM are different.

For crawler CM, such as crawler HE, the common working range of the engine is 1600–2000 rpm, which is at high-speed range relative to the whole speed range (0–2000 rpm). With a pure electric drive system, EM can make full use of its good speed regulation performance. The EM working speed range is wider than that of the original diesel engine, such as 500–3000 rpm. However, to ensure the operating performance of the electric crawler HE in its working range, it is generally required that the peak torque of the EM in its working range cannot be reduced too much.

4.2.3. Requirement for the ESU

To ensure the acceleration performance and reduce the installed capacity of the battery, the EV is sensitive to the weight of the battery. However, most of the CM itself needs to be equipped with a counter-weight to guarantee the whole machine's stability, so the requirement for the weight of the ESU is not high. Moreover, the charging speed of the battery required in the PECM is not high. The battery used in PECM is designed according to 2-h, 4-h and 8-h working day. The charging time for a 2-h working day is unlimited. While in the 4-h and 8-h working day, the charge is generally replenished between the lunch break (approximately 1–2 h) and the evening break (approximately 5–8

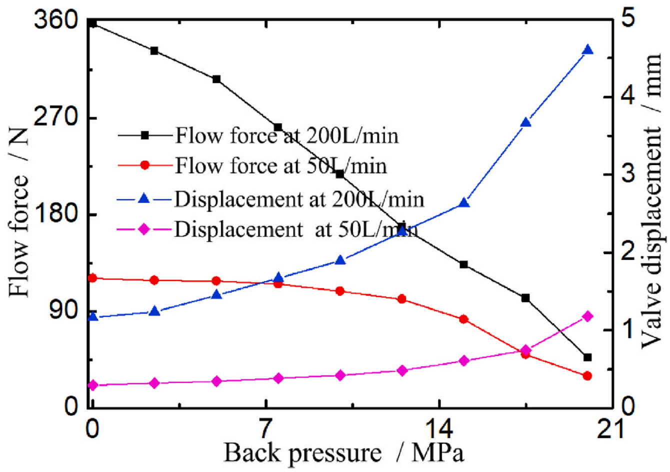


Fig. 6. Flow force and valve displacement changing eith the back pressure.

Fig. 7. Arrangement of the test rig to verify the proposed PRV with HERU [56].

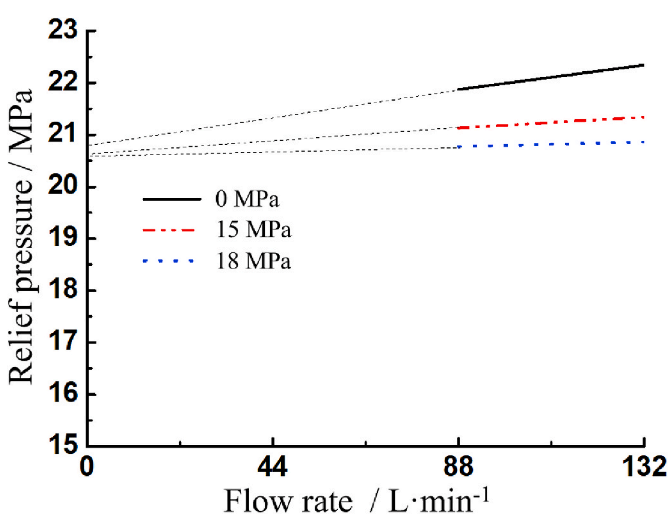


Fig. 8. Comparison of characteristics curves under different back pressure.

h). However, because the working conditions of the power unit of CM fluctuate very violently, the ESU experiences frequent large current charge and discharge. Therefore, the characteristics of high current high frequency response, safety and heat dissipation of the ESU are more important.

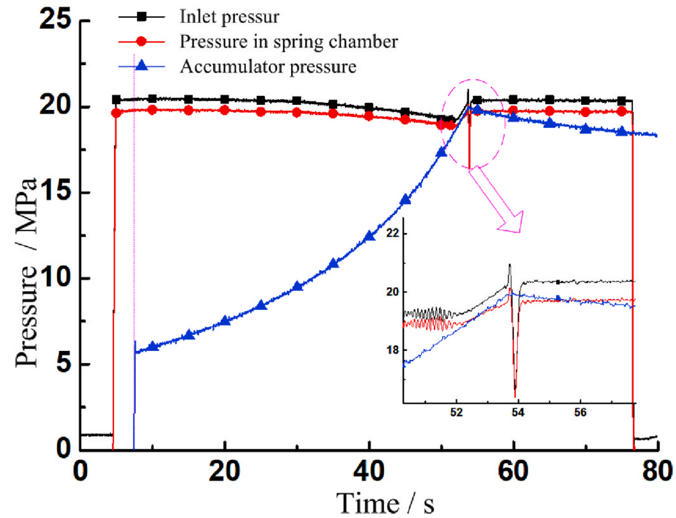


Fig. 9. Pressure curves of the proposed PRV during energy regeneration.

4.2.4. ERS

In EVs, the drive path and the regeneration path are the same systems, and the only load is to drive the wheel. When braking, the regenerative control strategy needs to coordinate the relationship between regenerative braking and friction braking to ensure the stability of the vehicle's braking performance and to avoid the danger of braking deviation and driving wheel locking caused by the change of weather, road condition and braking depth in the process of regenerative braking. While most of the CMs have multi actuators, and the driving path and the boom energy recovery path are generally two different systems, that are coupled by the electric ESU. At the same time, for HEs, during the process of arm braking and swing braking, the drive control strategy focuses on how to maximize the recovery energy under the premise of ensuring working performance, rather than to coordinate the relationship with the friction braking.

Therefore, it is not feasible to directly transfer the electric drive system and technology developed for EVs to the PECM.

4.3. Differences between the oil-electric hybrid CM and the PECM

At present, the application of the oil-electric hybrid power system in CM is already in the stage of prototype development [40]. It mainly adopts a parallel hybrid power system and the swing is driven by an EM. Because of the same application object, the related technology of the EM controller can provide a reference for the pure electric drive technology. However, compared with the EM used in pure electric conditions, there are still exist the following differences.

4.3.1. Different requirements for ESU

Due to EM different working modes, the hybrid power system and pure electric drive system used in CM have different requirements on the ESU. The hybrid power system requires less energy density of the ESU, and higher requirements for instantaneous large current charging and discharging [41]. While the ESU is mainly in shallow charging and discharging mode. However, for PECM, to ensure the fully charged operation time, the requirement for the energy density of the ESU is high [42]. At the same time, the ESU of PECM is basically in the deep charging and discharging mode, which makes the battery life more demanding.

4.3.2. Working principle

In the hybrid power system, the EM is mainly used to balance the fluctuation of the target torque of the load relative to the optimal working point of the engine [43]. The EM is necessary to constantly

Fig. 10. PEHE using AC power grid supply in HQU.

Fig. 11. Some other power grid type PEHEs.

switch between motor mode and generator mode, which requires that the EM power density is high- and the charging and discharging rate is fast. Moreover, EM operates intermittently. While in the PECM, EM is the only power source and has to operate continuously.

4.3.3. Control target

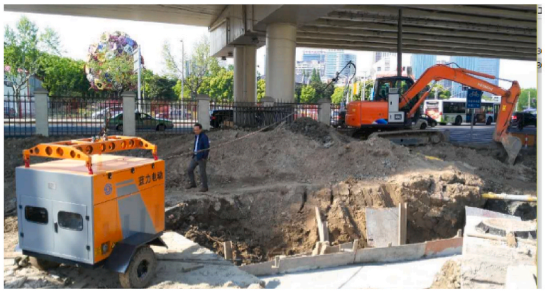
The EM operating speed in the hybrid system is mainly determined by the engine, which is 1600–2000 rpm. The EM mainly provides a wide range of electric torque and generating torque within a certain operating speed range [44] In a PECM, the EM is used to replace the engine. To better match the flow rate between the power source and load, the EM working speed is limited to 500–3000 rpm depending on the type of adopted hydraulic pump. The torque range is large too. And high torque is also required at a low speed. At the same time, the EM is required to operate in a higher efficiency range to avoid burning the EM and controller at low speed and high torque conditions. Driving system for PEHE not only needs to pursue high efficiency and overcome the bottleneck that restricts the development of pure electric drive, such as the working time and cost of a single charge of power battery, but also needs to ensure that the EM has good working characteristics in the wide range of speed and torque to make it suitable for different loads. Therefore, compared with the hybrid power system, the EM in pure electric system pursues more goals and changes with the load.

4.3.4. Working mode of the EM

In a hybrid CM, its engine is mechanically combined with the EM. The working speed is set by the engine. If the EM also works at speed mode, it will inevitably lead to the torque coupling disorder of the two power sources. Thus, the EM generally works in torque mode. While in the PECM, the working condition is more complicated and the power EM is expected to be able to work in the following modes.

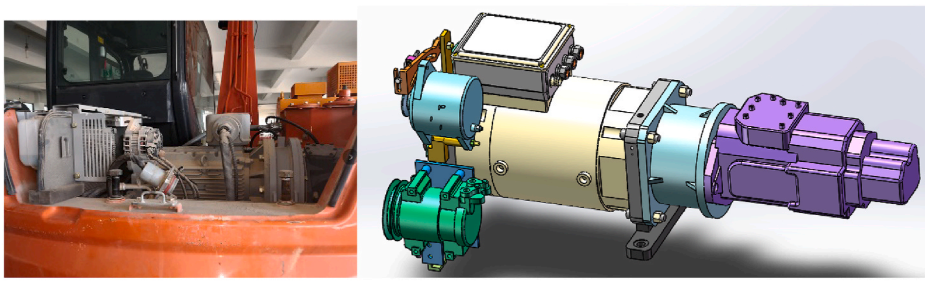
- Speed mode

Flow matching: Compared with the engine speed regulation, the variable frequency EM has advantages in dynamic response and speed control accuracy after the EM drive is adopted. To improve the efficiency of the hydraulic system, EM speed regulation is generally used to match



(a) PEHE of LANLI

(b) MPST of LANLI



(c) EM-pump assembly

Fig. 12. Electric excavator retrofit scheme of Hangzhou LANLI Electric Technology Co., Ltd.

Fig. 13. Pure electric excavator of Volvo EX2.

the flow rate of the hydraulic pump and that required by the load.

Pump pressure control: After the whole machine adopts the combination of load sensitive multiway valve + power EM + quantitative pump, when the load sensitive multiway valve detects the maximum load pressure, the hydraulic pump only needs to provide a pressure greater than the maximum load pressure, instead of flow control. Therefore, variable speed control based on the pump outlet pressure dynamic change and target pressure is also one of the EM speed modes.

Finishing operation: Refers to the slow and meticulous operation, such as lifting and lifting welding, etc. In this case, the required flow rate of the pump is small, but must be stable. Accordingly, the requirements for EM are the same.

- Torque mode

When a HE is excavating, the hydraulic system only needs to provide a large excavating force, while the output flow is very small. At this time, the EM works in a low-speed and high-torque mode. At this point, the outlet pressure mode of the hydraulic pump can also be equivalent to the EM torque mode. Meantime, when the automatic idling is cancelled, to quickly establish the maximum pressure required to overcome the load, the EM is generally driven with the target of the maximum load pressure

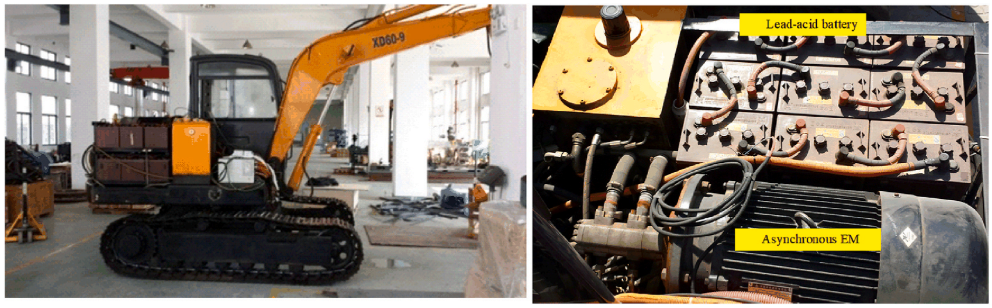


Fig. 14. A 6-ton PEHE using lead-acid battery.

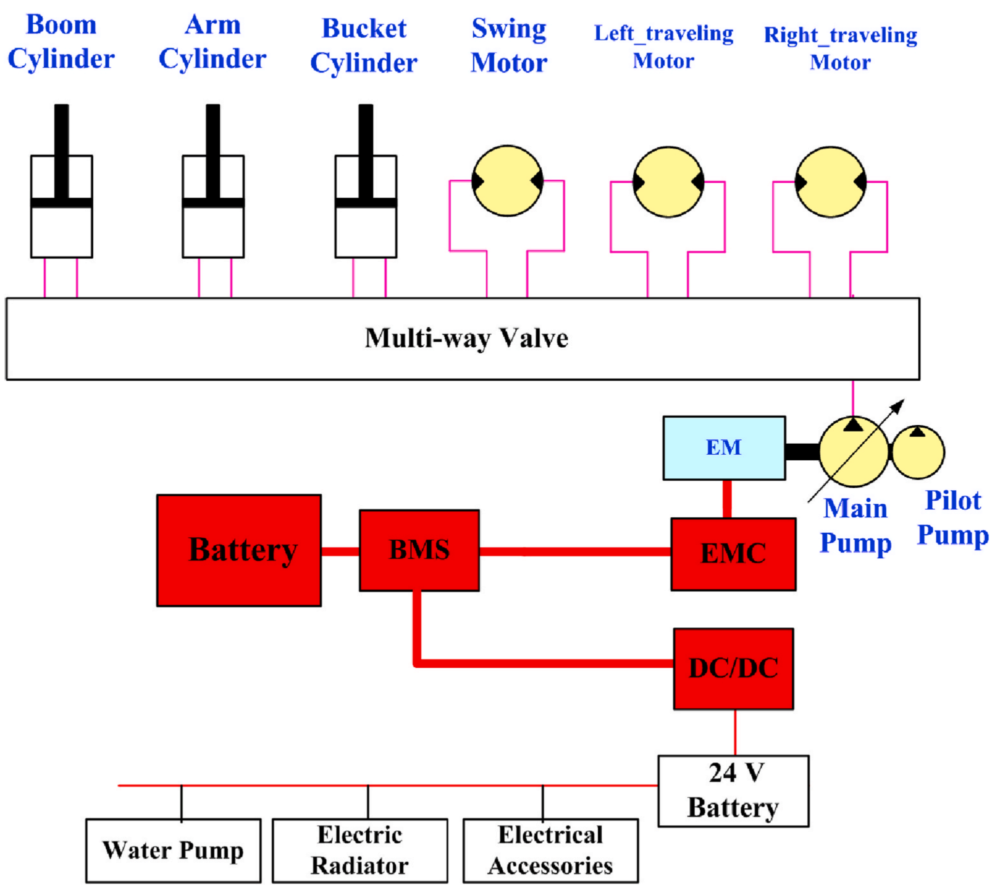


Fig. 15. System schematic of prototype PEHE using lead-acid battery.

Fig. 16. Photo of wheel PEHE using lithium battery.

[45,46], that is, the EM works in the torque mode.

(5) Higher requirements for reliability and safety

Compared with the hybrid CM, EM is the only power source of PECM. Moreover, PECM often works outdoors, it must ensure the safe and reliable mechanical device, reasonable circuit design, and stable and

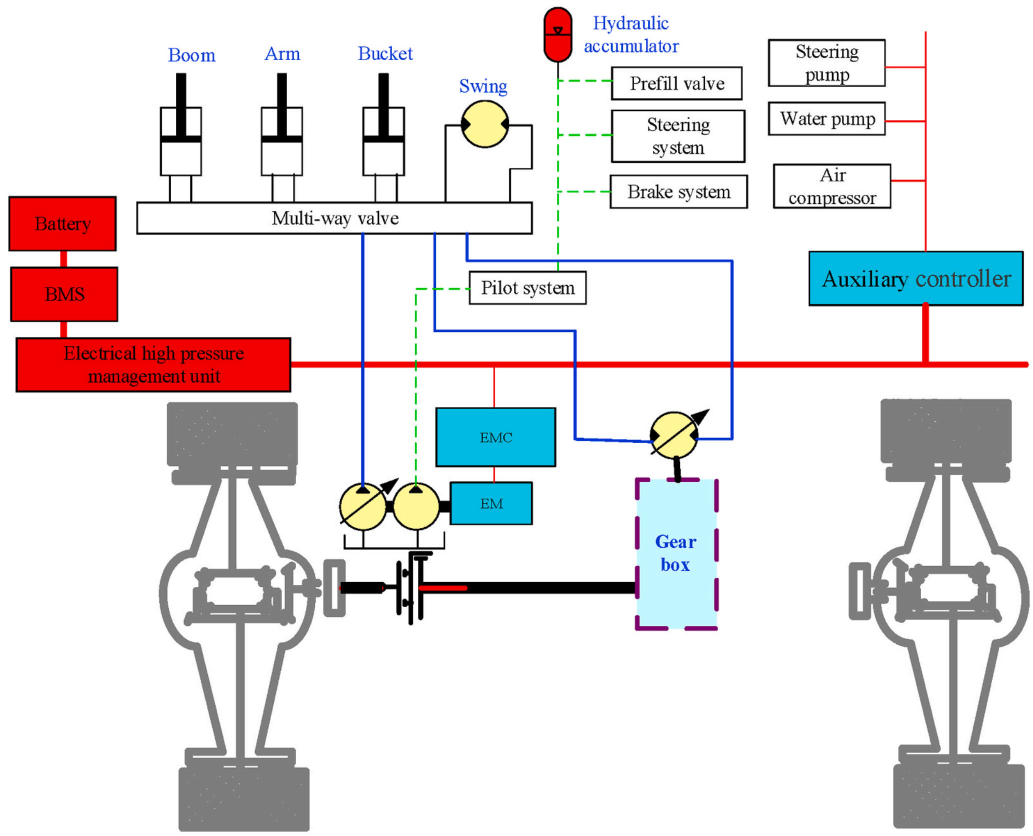


Fig. 17. Driveline layout of wheel PEHE using lithium battery.

secure software, as well as to ensure the minimum return distance of small CM. In addition, when some faults occur, the switching algorithm can be used to make the PECM drive to the safe area or the station for maintenance at the expense of certain operational performance. The switching process should ensure that the hardware circuit is not damaged and the CM can run smoothly after the switching.

5. Theoretical research on PECM

Although the pure electric drive system is widely used in industry and some technologies have been successfully applied to EVs, there are a few pure electric drive systems developed for CMs. The study on the powertrain of PECMs is less compared with that of EVs.

5.1. Structures and control strategy

Research of Professor Quan et al. [47] of Chinese Taiyuan University of Technology focused on PEHE. A constant speed EM and a variable frequency EM were utilized as a power source to drive a variable displacement pump of PEHE. The EM was powered by the cable. Compared with the constant speed concept, the variable speed concept consumes less electric power during the idle period. The consumed power is reduced from 2.05 kW to 0.7 kW and the energy-saving efficiency can reach 33% with partial load. Compared with the traditional HE, the proposed PEHE can save energy consumption by more than 30%.

To reduce the energy consumption and improve the control performance of a HE, Professor Lin et al. employed an EM to substitute the engine that drives the hydraulic pump [48]. Because the EM has excellent control performance and higher efficiency, a two-level idle speed control (ISC) system with a HA for a PEHE was put forward when ISC was cancelled. A control strategy utilizing co-simulation for the proposed two-level ISC was developed and tested. The results showed that the control strategy can make the EM speed switch automatically between the different idle speeds and normal working speed. Though the second idle speed in the PEHE is set much lower than that in a traditional HE, the actuator can still establish pressure rapidly when the EM is switched from ISC mode to normal working mode. Compared with a HE without ISC, the energy savings efficiency of the proposed PEHE was approximately 36.06%.

For efficiency optimization of PEHEs, Lee et al. developed a controller that considered both the EM efficiency and the hydraulic pump efficiency [42]. In a conventional HE, the hydraulic pump is driven by an engine that using regulators to optimize efficiency. Thus, efficiency maps of EM and hydraulic pump were built. The most efficient working points under each input condition were used to create an optimal working map. The EM speed and hydraulic pump displacement were controlled by an integrated control algorithm according to the created optimal working map. A simulator was established to verify the utility of this algorithm for the PEHE. And the results indicated that the energy efficiency of a PEHE can be improved by the proposed algorithm.

Jeong et al. focused on a hybrid energy accumulator including fuel cells and batteries that were used to support the EMs [49]. In the fuel cell hybrid excavator (FCHEs), the fuel cell undertakes most of the work, and the battery plays an auxiliary role. How much work the excavator can deal with depends on the battery capacity whose charging state must be considered when an effective strategy is used. An appropriate capacity ratio for the fuel cell and battery is important. Optimal capacity for them is suggested and a reference line for them is built.

In the long term, FCHE is an attractive option in the future. Li et al. presented a method for energy management and economy for a PEHE equipped with a fuel cell and supercapacitor [50]. The significant change in load laid major challenges on the FCS performance. Therefore, it is important to develop appropriate energy management strategies (EMSs) for FCHEs. MATLAB is used to verify the superiority of the proposed EMSs under cyclic loading for an excavator. The restrictions on

Fig. 18. LIUGONG's 6-ton crawler PEHE.

FCS power change were introduced to improve the FCS durability. The influence on hydrogen consumption caused by FCS and supercapacitor sizes were utilized to analyze the economy of the FCHE, as well as the use-cost. It indicated that the fuel economy of the FCHE is mainly affected by the FCS sizes. With the initial cost comes down, FCHEs will become more attractive.

Yi et al. studied the energy management of a PEHE equipped with supercapacitors. The power distribution profile was examined to compare the fuel cell, battery, and supercapacitor based on the required power profile of the engine driven excavator [51]. The fuel cell efficiency of a FCHE with supercapacitor was higher than that of a FCHE with the battery using the optimal control theory.

5.2. Hydraulic control system

As the electric drive system has already been applied to the HEs, Yoon et al. introduced an electro-hydraulic actuator to PEHEs [52]. Electric motor/generator is employed to drive the actuator to regenerate the potential energy or the kinetic energy of the excavator. To evaluate the proposed PEHEs, a 5-ton prototype excavator was developed to compare the performance of the system with a traditional boom system and the system with a hybrid boom system. Both the simulation and experiments were executed to verify the proposed control strategy on the 5-ton PEHEs to analyze the working efficiency and energy consumption.

Minav et al. studied the energy-saving methods of hydraulic systems. The boom, arm, and bucket of a 1-ton class JCB excavator controlled by valves were substituted by three independent direct-driven hydraulic units on [53]. They compared the efficiency improvement of the proposed decentralized hydraulics with that of an electrified conventional load sensing (LS) system. MATLAB/Simulink was used to simulate the above two systems. The results demonstrated that in a selected typical working cycle, the efficiency of the proposed direct-driven hydraulic was 71.3% and that of LS control was 18.3%.

Results of the design and application of new mechatronic systems with DC motors and transistor power transducers for mining excavators were considered by Malafeev et al. [54]. Intelligent motion control provided a dynamic performance and individual adjustment of drives, eliminating impacts and passing into critical zones. The application of modern DC motor transistor transducers made it possible to reduce power consumption by 20–30% compared to conventional excavators with Ward–Leonard drives and to reduce the specific power intensity of excavation. The power factor of the excavator was maintained and equal to a specified value in all operating modes, which ensured optimum electromagnetic compatibility of the excavator and a feeder line. New intelligent systems provided full control of all the key operating parameters of the excavator, loads on the working machine, working conditions, and the analysis and presentation of the basic technological parameters. Also, a remote monitoring module may be included in intelligent systems. Results of the design and experience in commercial production and operation of mechatronic systems for single-bucket mining excavators with transistor power transducers as a part of main motion electric drives were given.

5.3. ERS

ERS is not novel. Many ERS have been used with different kinds of energies in hybrid CMs. As the ERS in PECMs is similar to the ERS in

Fig. 19. LIUGONG's 20-ton crawler PEHE.

electric hybrid CMs. The research status of the electric and hydraulic ERS technologies for the CM's boom or the swing are not reviewed in this paper. The main energy loss that leads to the low efficiency of a hydraulic system is the throttling and overflow losses. The traditional energy regeneration technology of the hydraulic system is based on flow matching. Because the minimum throttle flow is the required flow of the actuator and the overflow flow is random, to reduce the hydraulic energy losses through reducing the flow has a certain limitation, especially in high-pressure hydraulic systems, one pump for multi-actuators systems and hydraulic systems with negative loads. What's more, reducing overflow loss is considered to be even impossible. The energy-saving of the hydraulic system is the research hot to reduce the energy losses in PECMs. Therefore, the ERS of the energy loss in the hydraulic system will be introduced [55-57].

The relief valve (RV) is widely used in hydraulic systems. Its overflow energy loss that relates to the pressure difference between the inlet and outlet attracts the interest these years. To reduce the energy loss and regenerate the energy of the RV, a hydraulic energy regeneration unit (HERU) is attached to the outlet of the pilot RV (PRV). Because the HERU can improve the PRV back pressure, the pressure difference before and after the valve port can be reduced, shown in Fig. 4. In the traditional PRV working conditions, the overflow energy directly flows into the reservoir, while in the proposed PRV with HERU, it can be stored in a HERU and can be discharged whenever it is needed. Through this process, the pressure loss through the PRV can be reduced.

The distributions of the velocity and pressure of the main valve are shown in Fig. 5. With the increase of the backpressure, the spool displacement of the main valve increase to make the flow rate keep constant, the pressure differential decreases from 21.5 MPa to 6.5 MPa and the maximum velocity flowing through the main valve is also reduced from 241 m/s to 120 m/s. Fig. 6 shows the change of the steady-state flow force and the valve displacement with the increasing of the backpressure. No matter the flow rate is 200 L/min or 50 L/min, with the increase of the backpressure, the steady-state flow force decreases and the valve displacement increases. And the larger the flow rate is, the lager the steady-state flow force and the valve displacement can be obtained.

The test rig shown in Fig. 7 is established to verify the feasibility of the PRV with HERU.

Fig. 8 shows the relief pressure changing with the flow rate under the backpressure of 0, 15 or 18 MPa, respectively. When the backpressure is 18 MPa, the pressure differential is only 2.5% while that of a traditional PRV is 15%. In other words, the higher the backpressure is, the smaller the pressure differential can achieve. When the flow rate through the PRV changes, a smaller pressure differential is helpful to improve the control accuracy.

Fig. 9 shows that when the PRV energy loss is regenerated by HERU, the HA pressure is increasing. The energy regeneration efficiency using HERU can reach 83.6%. This shows that the proposed PRV with HERU can obtain better working performance and higher regeneration efficiency.

6. Typical prototype PECM

The pure electric drive system is not a new technology, but different times have given it different meanings. In recent years, power electronics and ESU develop fast, along with increasingly strict emission regulations that various countries gradually phase out the engine. PECM

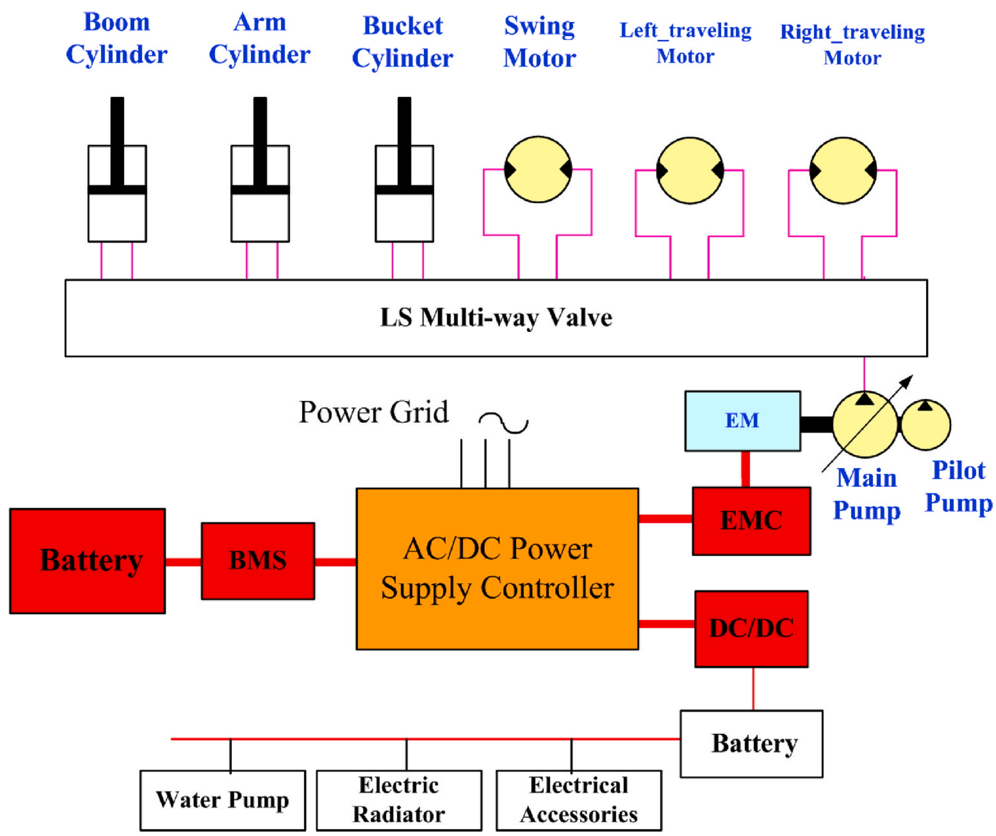


Fig. 20. Schematic diagram of crawler PEHE powered by power grid and battery.

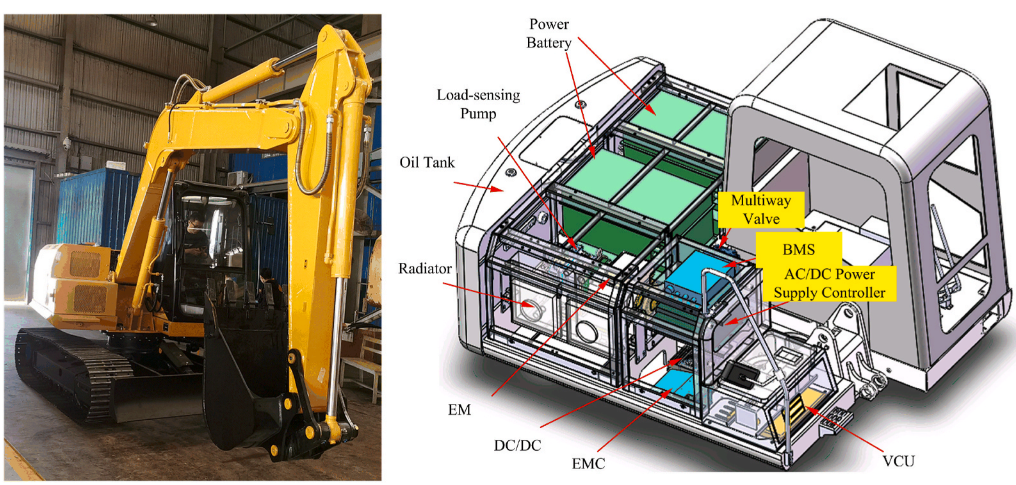


Fig. 21. Crawler PEHE powered by power grid and battery.

in the next few years will be on a fast track.

At present, Volvo, Hitachi, Komatsu, DOOSAN, Liebherr, Caterpillar, Liu Gong, Sunward, SANY, XCMG, XGMA, LANLI, SOCMA, Huaqiao University (HQU), Zhejiang University, Taiyuan University of Technology, etc, all devote themselves to the PECM. A number of experimental models of the PECMs had been developed. For reasons of commercial confidentiality, specific details of the prototypes cannot be made public.

6.1. PEHEs

6.1.1. Prototype of power grid type PEHE

Nowadays, most of the enterprise retrofit the traditional excavator to an electric one that is powered by the power grid. The diesel engine is removed directly and replaced by an EM that is powered by the power grid. This retrofitting is based on the power grid. The PEHE can work continuously only if supply the power grid to it. This type needs a cable to supply the power from the power grid that restrains the flexibility of the excavator and is not suitable for the places where there is no power grid. Shown in Fig. 10, it uses the power grid to supply directly, not the power battery. There are two core parts of PEHE supplied by the power grid. One is the powertrain control technology that uses a servo EM instead of an engine to drive a hydraulic pump. Another is how to ensure that the swing mechanism of the PEHE can rotate at any angle. The hydraulic system of the whole machine is basically unchanged. There is

Fig. 22. Breton BRT951EV PEWL

no energy recovery. The hydraulic oil radiator is driven by a hydraulic motor. Furthermore, the water-cooling system of the original engine is used to cool the EM and controller. A separate asynchronous motor is used to drive the air compressor for air conditioning. It consumes approximately 30 kWh per hour. This type of excavator is suitable for the occasions where it is convenient to get electricity from the power grid.

At present, Komatsu, DOOSAN, Sunward, SANY, Liebherr, Caterpillar, et, all launched this kind of PEHE (seen in Fig. 11). Seen from Fig. 11(d) and (e), the power supply device of the grid had been specially designed to ensure that the cable will not affect the HE rotary motion. For the large tonnage class HEs that are used in mine construction, the EM power is very larger. If the EM is powered by the battery, the capacity of the battery will be very large and the cost is high. Hence, the large tons of PEHEs are commonly supplied by the power grid (seen in Fig. 11(a), (c) and (e)).

6.1.2. External power type PEHE

This type is proposed by Hangzhou LANLI electric technology Co., Ltd at Bauma China, Shanghai, November 22th, 2016. LANLI launched an electric excavator with a separate high voltage power supply to ensure a long working capacity, shown in Fig. 12(a). MPST shown in Fig. 12 (b) was specially designed to ensure a continuous supply for PEHE. However, this only provides a kind of commercial operation mode of electric transformation of excavators and doesn't put forward the key technologies to solve the problems during the electrification of CMs. The experimental results proved that the fuel consumption is approximately 30 kWh per hour. Wacker Neuson also previewed similar PEHE (see Fig. 13).

6.1.3. Prototype of Battery type with no hydraulic system

Looking at the development of pure electric technology in Volvo Construction Equipment, it held an innovation summit in London, UK, where it launched a PE excavator EX2 (Fig. 13) on May 16, 2017. EX2 uses two lithium-ion batteries whose capacity is 38 kWh to replace the internal combustion engine. EX2 can operate for approximately 8 h on a full charge. The main feature of EX2 is that the hydraulic system is also

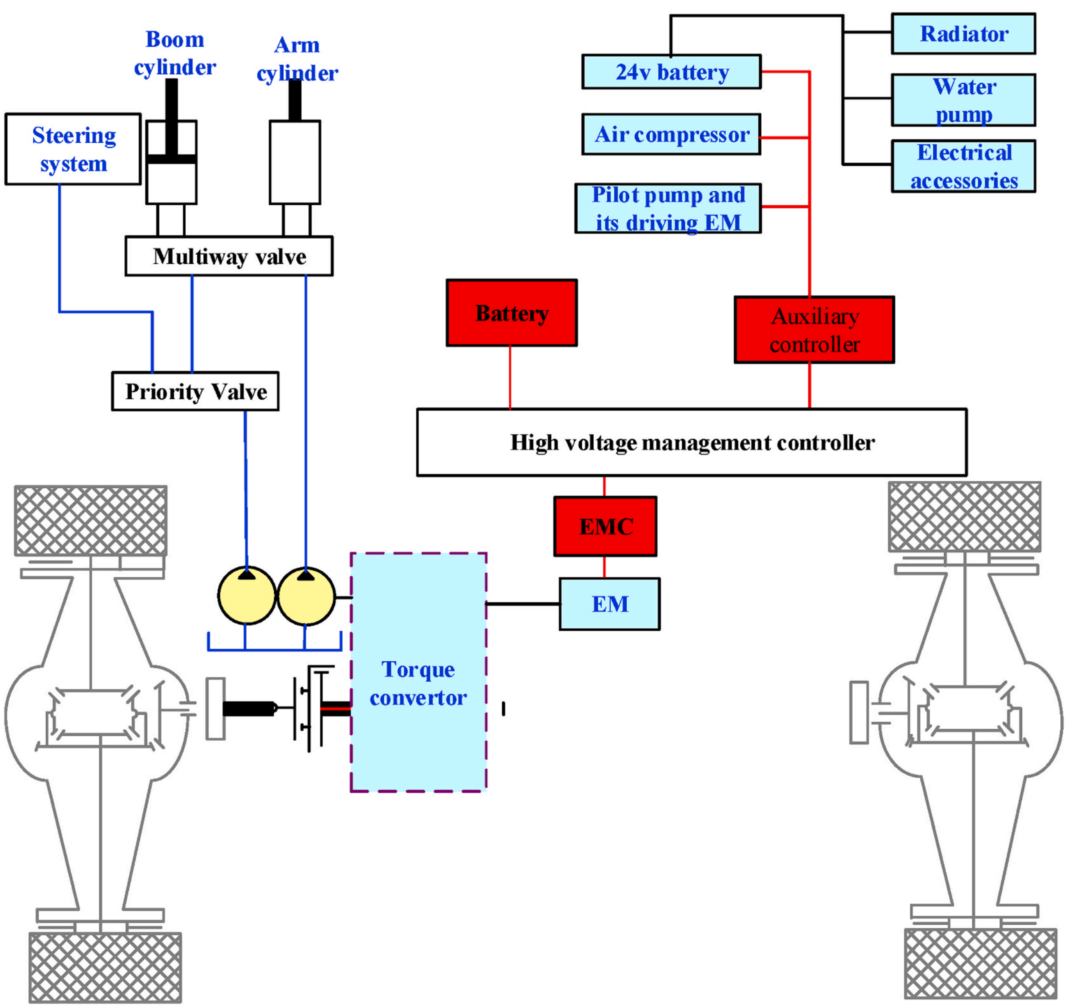


Fig. 23. System outline of Breton BRT951EV PEWL.

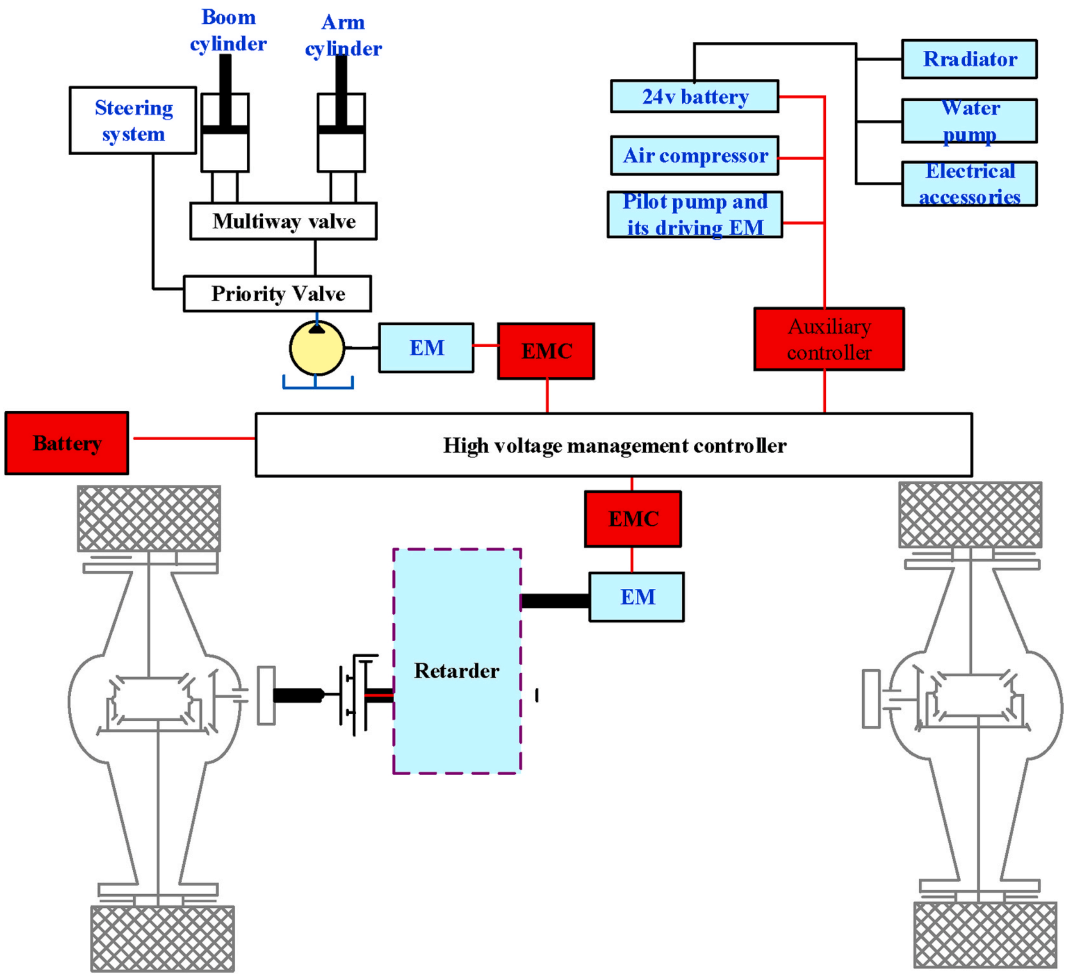


Fig. 24. Schematic diagram of 1.6-ton PEWL.

Fig. 25. Picture of 1.6-ton PEWL

replaced by the electrical components. That is to say, the hydraulic cylinders of the boom, arm, and bucket had been replaced by three electric cylinders. The swing system and the walking system are also driven by pure electric. Then the noise produced by the hydraulic system and the engine can be avoided. This EX2 can realize the zero-emission and reduce noise levels by 10 times. However, limited by the power of the electric cylinder, this scheme can only be used in small tonnage CMs, and this model is only for the company's research project.

6.1.4. Prototype of Battery type with hydraulic system

In 2013, a 6-ton HE driven by pure electric was developed in HQU, shown in Fig. 14. The system schematic of the developed PEHE using a lead-acid battery is shown in Fig. 15. Considering the energy density requirement of the pure electric drive system and the charging speed requirement under energy recovery condition, a high-power lead-acid battery was adopted as the ESU for this model. The battery capacity is 300 V, 210 Ah. A 40-kW asynchronous motor was adopted to drive the pumps. The rated speed and the peak speed of the EM are 2010 rpm and 3000 rpm, and the rated torque and peak torque of the EM is 190 N m and 400 N m, respectively. A DC/DC convertor was equipped to charge the 24 V battery for this PEHE. This prototype consumes approximately 35 kWh per hour. The main advantages of it are simple structure, low cost, while the disadvantages are slow charging, low efficiency, and a large volume because of the lead-acid battery.

In 2017, HQU, in collaboration with XGMA and SOCMA, launched a wheel PEHE again that is close to commercial application, shown in Fig. 16 and Fig. 17 presents the driveline layout of wheel PEHE using a lithium battery. The integrated unit of a servo EM and a variable pump is adopted. An electric pilot pump is used separately. The accessories of the whole machine, such as electric pilot pump, electric air compressor, electric radiator, etc, are driven independently by a special auxiliary controller drive. The ESU uses a ternary lithium battery with a battery capacity of 110 kWh and a battery voltage rated 550 V. Through the pressure detection port LS of load sensitive multiway valve, the pressure signal is fed back to the EM controller to make the EM control the load sensitive pressure to feedback. The variable constant-power control strategy is used. Through flexible EM control, the response of the output

Fig. 26. LIUGONG's 5-ton PEWL

pressure of the pump can be improved. The dynamic response time of the special electric motor-pump is within 150 ms. Through a reasonable combination of displacement and speed, the pump and motor can work in a comprehensive high efficiency area. Fuel savings were recorded at around 75% in comparison to the standard engine HE. The total power consumption is only approximately 12–15 kWh per hour.

At BICES 2019, LIUGONG presented a 6-ton crawler PEHE and a 20-ton crawler PEHE, respectively. As shown in Fig. 18, LIUGONG's 6-ton electric crawler excavator is a modified version of the original diesel-driven excavator. It uses the hydraulic system of the original diesel-driven excavator. At the same time, it is equipped with a large-capacity battery package, which can meet the need of one day's full-time work. As shown in Fig. 19, LIUGONG's 20-ton electric excavator is a redesigned model. To ensure continuous mileage of the machine, the body is equipped with a battery capacity of 430 kWh. The weight of the machine is redesigned and the volume is large. A camera is specially configured in the rear body to meet the blind line of sight caused by the battery arrangement. At the same time, the machine also has a boom potential energy recovery device, which recovers and reuses the potential energy and kinetic energy during the boom moving down, and thus the continuous mileage of the machine is extended.

6.1.5. *Prototype of battery and grid power supply type*

In view of the characteristics of inflexible moving of crawler HEs, HQU, in collaboration with SOCMA and Hitachi, launched an 8-ton crawler PEHE that was supplied by the power grid and battery in 2019. Fig. 20 shows the schematic diagram and Fig. 21 is the physical prototype. This PEHE can be powered by the power grid alone, lithium battery alone and both of them. The battery capacity can be selected according to the actual work demand. The working principle of other parts is similar to the wheel PEHE shown in Fig. 16. At present, this type of excavator is introduced in Hitachi, XGMA, and SOCMA.

6.2. *Pure electric wheel loader*

In 2019, Breton introduced a pure electric loader BRT951EV that uses a big EM instead of a traditional diesel engine, shown in Fig. 22. Fig. 23 shows that the torque converter and hydraulic system are retained. This type of loader is suitable for ports, mining areas, steel and coal fields, especially for sand and concrete industries. The efficient drive EM and the mature two-variable system can respond in milliseconds to make the EM power source more direct. It can achieve zero-emissions and no pollution. This model consumed approximately 35 kWh per hour.

In 2019, SOCMA and HQU jointly developed a 1.6-ton pure electric wheel loader (PEWL), shown in Fig. 25 and Fig. 24 is the schematic diagram of the 1.6-ton PEWL. Seen from Fig. 24, the low efficient torque converter is eliminated. Hydraulic systems for working and walking systems are driven by two independent EMs. The experimental results show that the PEWL consumes 11 kWh per hour, and the traction force is 64 kN. As shown in Fig. 26, the 5-ton PEWL developed by LIUGONG has an EM that the peak power is more than 300 kW, it has a strong explosive force and pusher performance. A large 300-plus kWh battery package is installed at the rear and replaces the traditional counterweight.

In 2019, an extended-range PEWL (shown in Fig. 27 and Fig. 28) was proposed to solve the disadvantages that the large tonnage loader

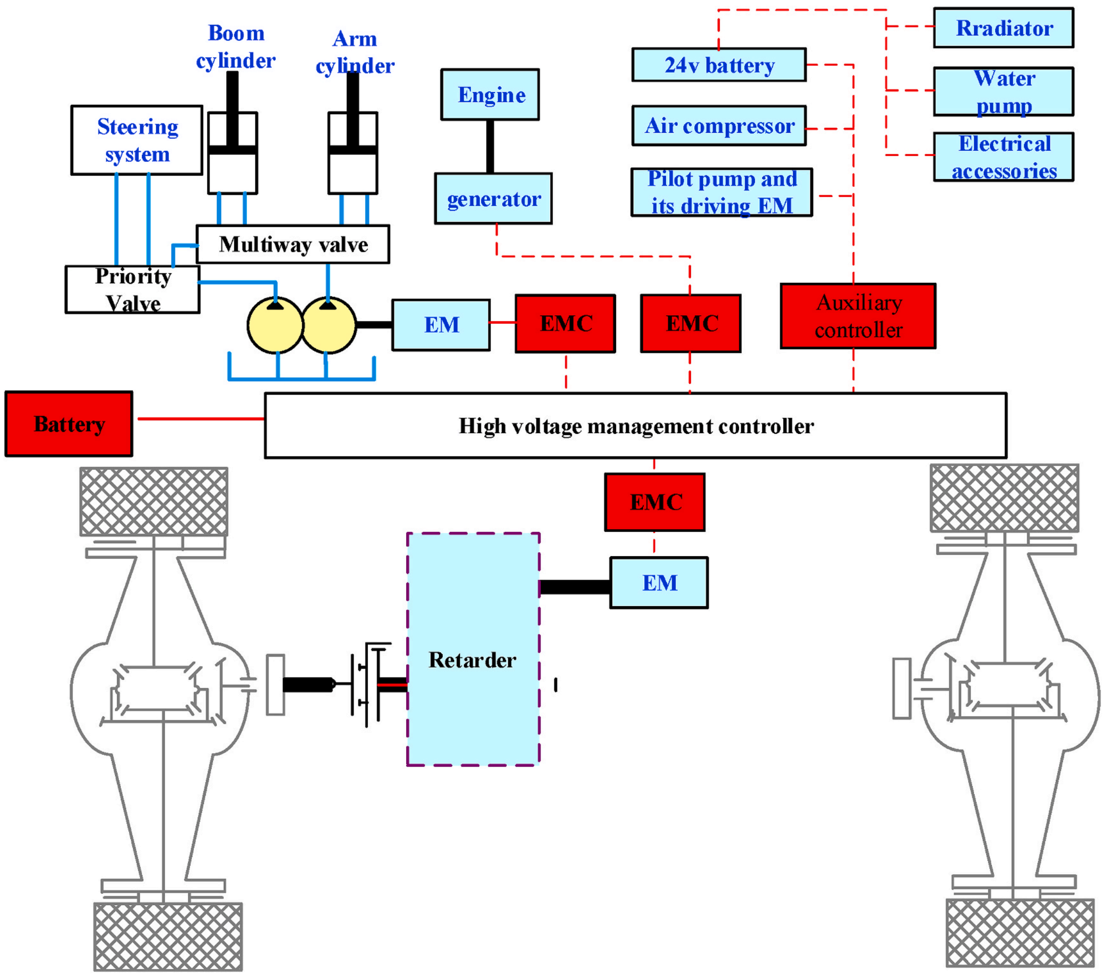


Fig. 27. Schematic diagram of 5-ton extended-range PEWL.

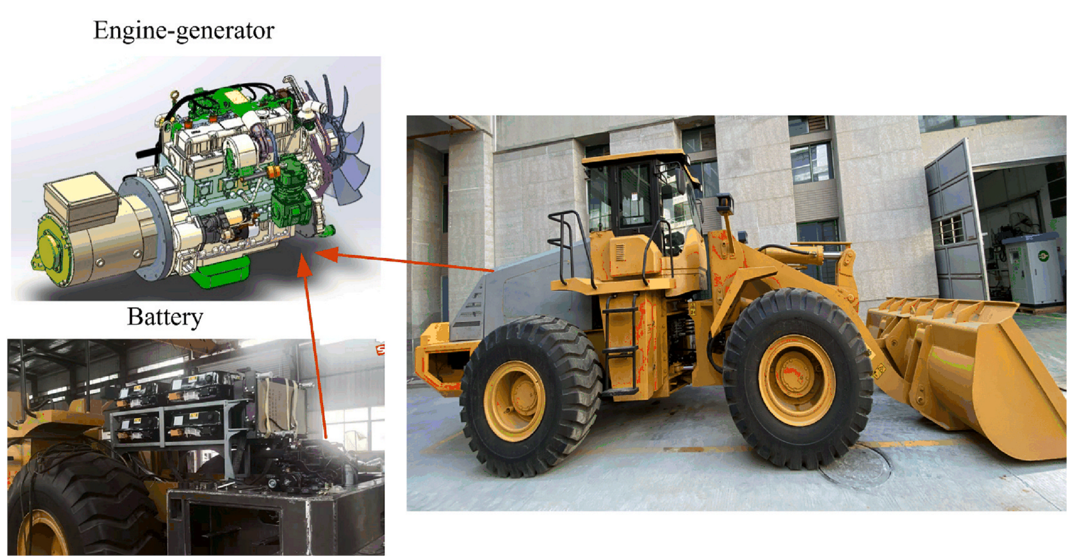


Fig. 28. Photo of 5-ton extended-range PEWL.

requires a large battery capacity. This loader was equipped with a 38-kW diesel generator and a set of 110 kWh battery. It can meet the working demand of more than 8 h after fully charged, and consumes approximately 30 kWh per hour.

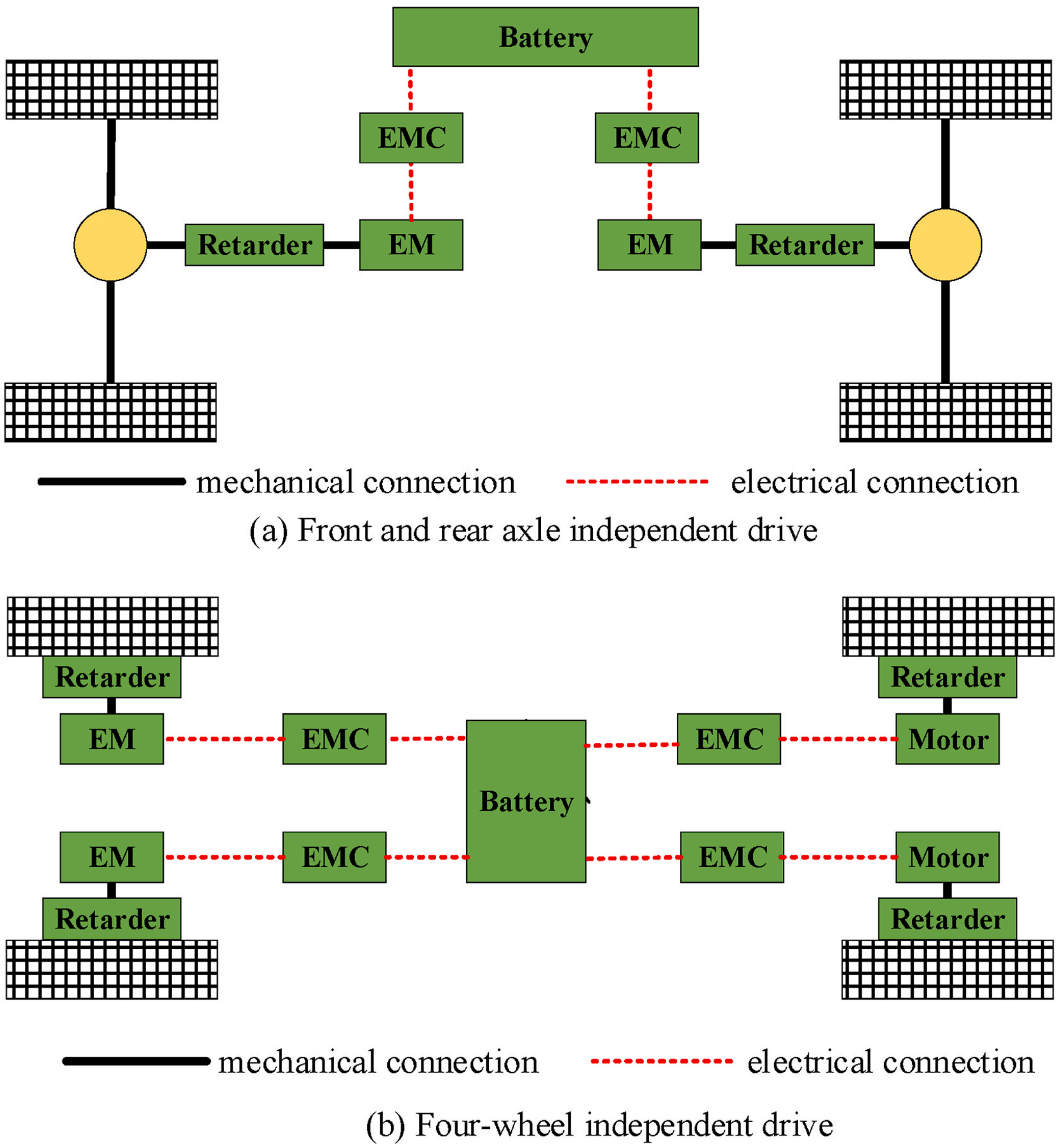


Fig. 29. Distributed PEWL

7. Challenges

7.1. New hydraulic components and systems based on electric drive technology

Compared with the dynamic response of diesel engine that is usually several hundred milliseconds, the EM has better torque and speed control characteristics and has a faster dynamic response that is usually several milliseconds to tens of milliseconds. The hydraulic drive is generally adopted due to the larger power level of the CM. The existing hydraulic control technology is chosen to match the characteristics of a diesel engine, but does not match well with the electric transmission technology. The main problems are as follows.

(1) The design of hydraulic pump is mainly based on constant speed and variable displacement control. The high efficiency range and dynamic response of the hydraulic pump cannot meet the requirement of frequent acceleration and deceleration of the EM in a large speed range. Take the excavator as an example, the high efficiency range of the hydraulic pump is mainly concentrated around 1800 rpm, and the flow matching is more based on variable displacement control. While after the electrification of the CM, the operating speed range of the hydraulic pump is even larger. How to ensure that the hydraulic pump has high efficiency, high frequency response and high reliability in the large speed range are one of the technical challenges to overcome.

(2) At present, the CM hydraulic system, such as LS system, negative flow system, and positive flow system, etc, uses the multi-way valve to match the variable-displacement pump mechanism. How to adapt to the variable-speed variable-displacement or variable-speed constant-displacement system is also a problem to be solved.

(3) For the actuators, it is possible to carry out the distributed independent drive control because it has an electric ESU after the electrification of the CM. And it can even be directly driven by the electric cylinder. However, limited by the power level of the existing electric cylinders, to study the new electro-hydraulic linear compound drive actuator based on the advantages of the hydraulic system is an important problem to be solved.

Therefore, according to the CM working conditions and the advantages of electric transmission technology, to study the new hydraulic transmission and control technology compounded with the electric transmission is significant.

7.2. Novel powertrain configuration challenges

For wheel loaders, distributed PEWL may be the next development in the future. It includes two types shown in Fig. 29: one type is the front- and rear-axle independent drive and the other is the four-wheel independent drive. Besides the save energy, the distributed PEWL can also control the driving force to improve active safety and working performance. However, to reach this goal, it is firstly required to identify the wheel loader operating environment. This involves the state estimation of the key parameters of the whole machine. While further development is needed to better study the state estimation on CM.

7.3. Energy storage devices challenges

Recently, engines used in vehicles and CM have been removed and substituted by alternative power sources, such as batteries, fuel cells, and supercapacitors. The only mass-produced EV is equipped with the batteries, while the developed fuel cell EVs are the hybrid of the fuel cell and the battery. The energy management and optimization for the hybrid EVs are developed to minimize the total running cost [58–62]. The EVs powered by the lithium battery cannot serve the long-distance, low cost, and highly efficient transportation markets well. To make full use of the PECMs, the properties, like specific energy, cost, safety, and compatibility with power grid, should be improved.

Generally, a combined energy storage system can fully use the high specific energy of one device and the high specific power of the other. A combined ERU composed of a HA and a battery is suitable for PECMs because most of the actuators in the CM use the hydraulic drive system. The greatest advantage to use HAs in CMs is that they can be integrated into a hydraulic system seamlessly. The advantage of this system is that the CM can be powered by the battery and the HA at the same time. It can prolong the energy recycling time through a control strategy. Moreover, it can use a HA to substitute the supercapacitor because of the power density of a HA is similar to that of the supercapacitor. Moreover, hybridization of the energy storage system has a great influence on power utilization and can promote the development of the technologies.

7.4. Safety and reliability

Compared with traditional fuel oil drive technology, the pure electric drive has incomparable advantages, but it also brings other problems. High temperature, greater than 10 g vibration and high voltage are the main factors affecting the safety and reliability of PECM. Taking high temperature as an example, when the battery is installed in the chassis of a CM, the most notable technology is the safety of the battery. For example, the operating temperature of power batteries is generally between 20–60° [63,64], while the CM often operates in situations where the ambient temperature is more than 40°. In such a harsh environment, the safety of PECM should be ensured. Furthermore, as to vibration and impact resistance, the automobiles need to sustain approximately 5–7 g, while that for CMs is more than 10 g. In fact, the switching actions of the EMC designed for the working conditions of PECM would seriously affect the electromagnetic compatibility of the whole machine.

7.5. Acceptable cost

Today's PECMs are almost equipped with lithium-ion batteries, however it will take PECMs a long way to dominate the global market. Except for the policy support, PECMs also require high-performance and low-cost technologies to promote its widespread development. Compared with traditional CM, components employed in an electric system can increase the initial cost of the PECMs. While the initial cost directly affects the acceptability and recognition of the public. Compared with large tonnage CMs, it is more severe for small tonnage CMs. In general, the price of PECM will be 2 to 3 times of a traditional CM at first. Thus, there is a large room for the cost to come down to the equivalent level of the same class traditional CM. With the emergence and convergence of new technologies, pure electric is promising to reduce costs.

8. Conclusions

The electrification of CMs is the focus of this discussion. The types and characteristics of energy storage components, Ems, and pure electric drive system are analyzed. The key technologies and difficulties in the electrification of CM are explored. The application differences of EMs and controllers between the other fields and CM are introduced. The developing PEHE or PEWL demonstrated the potential benefit of this technology. A variety of new PEHEs and PEWLs are introduced based on the prototypes. With the market demands and policy orientation for PECM, the earthmoving equipment manufacturers will continue devoting themselves to developing cheaper, more efficient PECMs.

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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