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Research on Energy Efficiency Characteristics of Mining Shovel Hoisting and Slewing System Driven by Hydraulic-Electric Hybrid System

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Abstract

Mining shovel is a crucial piece of equipment for high-efficiency production in open-pit mining and stands as one of the largest energy consumption sources in mining. However, substantial energy waste occurs during the descent of the hoisting system or the deceleration of the slewing platform. To reduce the energy loss, an innovative hydraulic-electric hybrid drive system is proposed, in which a hydraulic pump/motor connected with an accumulator is added to assist the electric motor to drive the hoisting system or slewing platform, recycling kinetic and potential energy. The utilization of the kinetic and potential energy reduces the energy loss and installed power of the mining shovel. Meanwhile, the reliability of the mining shovel pure electric drive system also can be increased. In this paper, the hydraulic-electric hybrid driving principle is introduced, a small-scale testbed is set up to verify the feasibility of the system, and a co-simulation model of the proposed system is established to clarify the system operation and energy characteristics. The test and simulation results show that, by adopting the proposed system, compared with the traditional purely electric driving system, the peak power and energy consumption of the hoisting electric motor are reduced by 36.7% and 29.7%, respectively. Similarly, the slewing electric motor experiences a significant decrease in peak power by 86.9% and a reduction in energy consumption by 59.4%. The proposed system expands the application area of the hydraulic electric hybrid drive system and provides a reference for its application in oversized and super heavy equipment.

Keywords Mining shovel, Hoisting and slewing system, Hydraulic-electric hybrid drive, Energy saving

1 Introduction

Mining shovel is a vital piece of important equipment for open-pit mining. In the working operation, the bucket loads minerals under the cooperation of the hoisting device and the pushing mechanisms. Subsequently, the hoisting device lifts the bucket to the unloading height. At the same time, the rotating mechanism drives the slewing platform to the unloading position. After unloading, the bucket will fall back to its initial position. During the falling process of hoisting device or the decelerating process of slewing platform, the driving motors enter a power generating state. The electricity generated by the hoisting motor or the slewing motor is dissipated in the form of thermal energy through brake resistance. The hoist, the bucket, and the slewing platform are all substantial in weight, leading to significant wastage of electric energy. Take the hoisting device falling process of a shovel with a 12 m^3 bucket capacity as an example, when the hoisting device falls from the unloading position to the vertical position, the change of gravitational and potential energy is 1388 kJ. Assuming the device works 20 h a day with a cycle time of 30 s, the electric energy

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waste amounts to a staggering 833 kW·h per day. This is equivalent to the electricity consumption of an average household for two months.

In addition, to meet the instantaneous power requirements during the excavation of the hoisting device and the acceleration of the slewing platform, the motors must be configured according to the peak power. Taking the hoisting device as an example, the installed power of the hoisting motor for the mining shovel with 12 m^3 bucket capacity reaches 560 kW. As a result, the hoisting motor works in low load state more frequently, and the configuring motor according to the peak power results in prolonged periods of low-efficiency conditions. This, in turn, increases the weight of the motor and the cost of the controller while diminishing overall the energy efficiency of the motor. Therefore, under the premise of ensuring normal production efficiency, recycling the gravitational potential energy and kinetic energy of the shovel working device, and reducing the installed power of the hoisting motor and slewing motor, will greatly cut down the energy consumption and production cost of the shovel [1].

To recycle and utilize the gravitational and potential energy and kinetic energy of the shovel, the ultracapacitor energy storage mode and feedback grid mode are adopted in the shovel driving system. Caterpillar Company of the United States and Siemens Company of Germany jointly applied for the patent of energy storage technology which replaces brake resistance with ultracapacitor to store the potential energy [2–4]. An AC-DC hybrid driving solution that used an ultracapacitor to compensate for the peak current was proposed [5, 6]. In the [7–9] research, the energy stored in the ultracapacitor can also compensate for the peak current of the hoisting motor, reduce its interference to the power grid, and decrease operation energy consumption. Similarly, Taiyuan Heavy Industry applied for the invention patent of the shovel AC frequency conversion speed regulating device and its control system [10]. In the patent, when the hoisting device was falling, the electricity from the hoisting motor drives other motors through the common DC bus, and the redundant part feeds back to the power grid. The energy feedback device of the AC variable frequency speed regulation system was studied in Refs. [11, 12]. In the speed regulation system, the electric energy from the hoisting motor was directly fed back to the power grid during the falling process of the shovel hoisting device. In addition, a kind of feeding system of the shovel was simulated in Ref. [13]. The simulation results of the feeding system show that the energy saving of the shovel was about 25%.

Also, by optimizing the hydraulic system [14], mechanical structure [15] and bucket excavation trajectory [16], the purpose of energy recycling and utilization could be achieved. The team of Professor Quan of Taiyuan University of Technology adopted the double closed circuit hydraulic system to control the slewing platform of the hydraulic shovel in parallel, and the slewing motor was directly controlled by electro-hydraulic proportional pumps, which eliminated the overflow and throttling loss of the system [14, 17, 18]. By optimizing the power supply system of shovels in open-pit mining, the operational availability, and energy efficiency were improved [19]. By optimizing the bucket structure, the digging resistance was reduced and the efficiency of shovel operation was improved [20]. In Ref. [21], through dynamic simulation, the relationship between shovel structure parameters and bucket payload was determined, and the shovel structure was optimized to improve production efficiency. In Ref. [22], the mathematical model of excavating force and energy consumption was established, which provided a basis for track optimization and energy consumption analysis.

In summary, the supercapacitor energy storage system necessitates the combination of multiple large-capacity and large-volume supercapacitors in series and parallel, resulting in significant space occupation, numerous conversion links, and limited improvement in energy efficiency [23]. Feeding energy into the grid is technically complex, costly, and it also causes harmonic interference to the high-voltage grid. Improved structure and optimized trajectory, limited improvement in system energy efficiency and susceptibility to external working environment [24].

Summarizing the above research work, in the scheme of feeding energy to the grid, the electric energy from the hoisting motor can only be fed back to the high-voltage grid through the active inverter circuit. For high-voltage motors, the feedback power technology is complex and costly, and it also causes harmonic interference to the high-voltage grid. In the scheme of the ultracapacitor energy storage system, a large number of ultracapacitors need to be combined in series or parallel and be used for energy recovery of large-capacity equipment with high-voltage after DC-DC boost. Besides, the efficiency of the schemes is low when the motor is generating and the reduction range of installed motor power is small. The optimization method of improving the shovel's hydraulic system, structure, and trajectory has a limited energy-saving effect and is easily affected by the change of external environment.

Aiming at making full use of the kinetic and potential energy and improving the safety of the mining shovel, this paper proposed an innovative hydraulic-electric hybrid driving principle by coaxially connecting the hoisting motor and hydraulic pump/motor. The structure of the

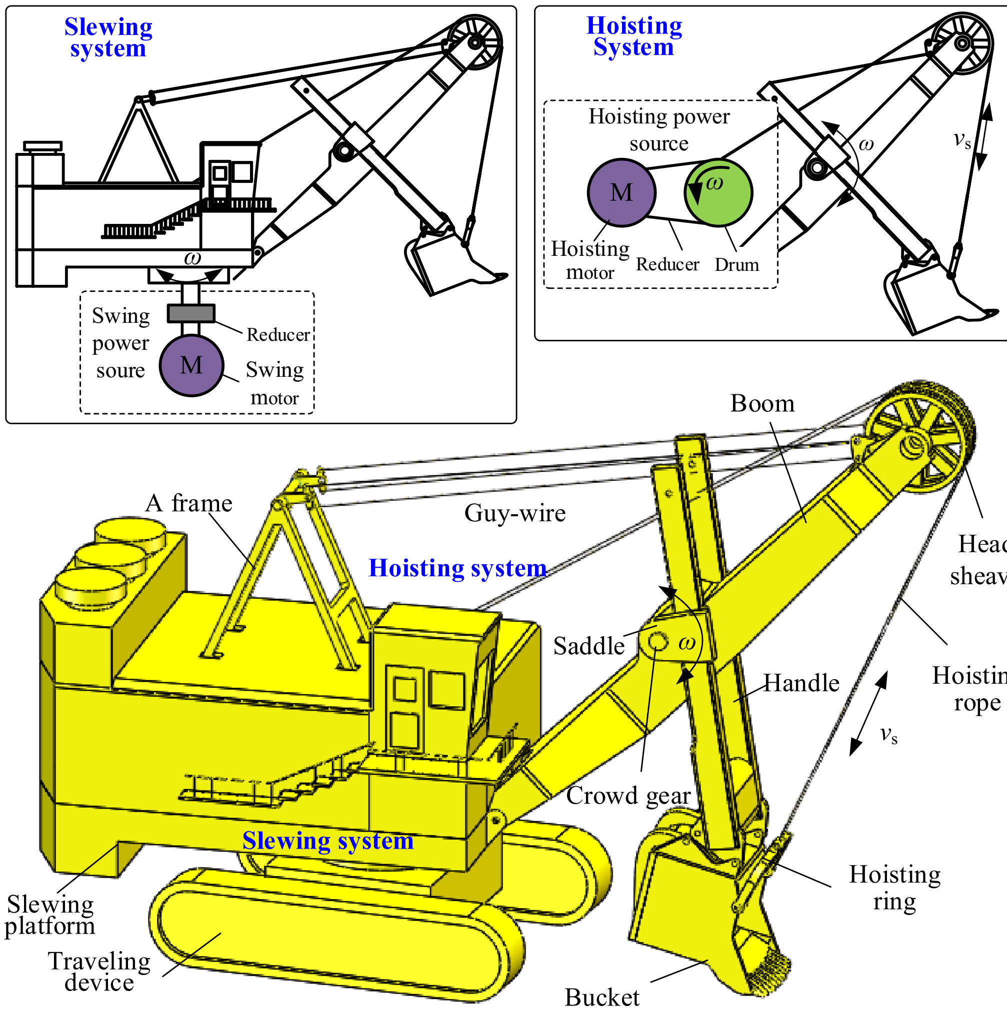


Figure 1 Composition and structure of mining shovel

proposed system is shown in Figure 1. The inlet and outlet of the hydraulic pump/motor are respectively connected with the hydraulic accumulator and the oil tank. When the hoisting device is falling or the slewing platform is decelerating, the hydraulic pump/motor works under pump conditions and pumps the oil from the tank to the accumulator, transforming the gravity potential energy of the hoisting device and the kinetic energy of the slewing platform into hydraulic energy and storing in hydraulic accumulator. When the hoisting device is lifting or the slewing platform is accelerating, the hydraulic pump/motor works under motor conditions, the accumulator releases high-pressure oil, and the hydraulic pump/motor drives the devices together with the electric motor, to reduce the peak power and energy consumption of the electric motor. And the security of the system has been improved.

This paper is organized as follows. The working principle of the hydraulic-electric hybrid driving electric shovel hoisting and slewing mechanism is introduced in Section 2. Section 4 presents the theory analysis of the hydraulic-electric hybrid driving shovel. In Section 4, the principle test platform is set up to verify the hydraulic-electric hybrid driving principle. Learning from the mature digital prototype modeling theory and method of the team [25–28], the co-simulation model of the hydraulic-electric hybrid driving electric shovel is established in Section 5. The influence of accumulator parameters on the hoisting device of the hybrid driven shovel is described in Section 6. Section 7 is conclusions.

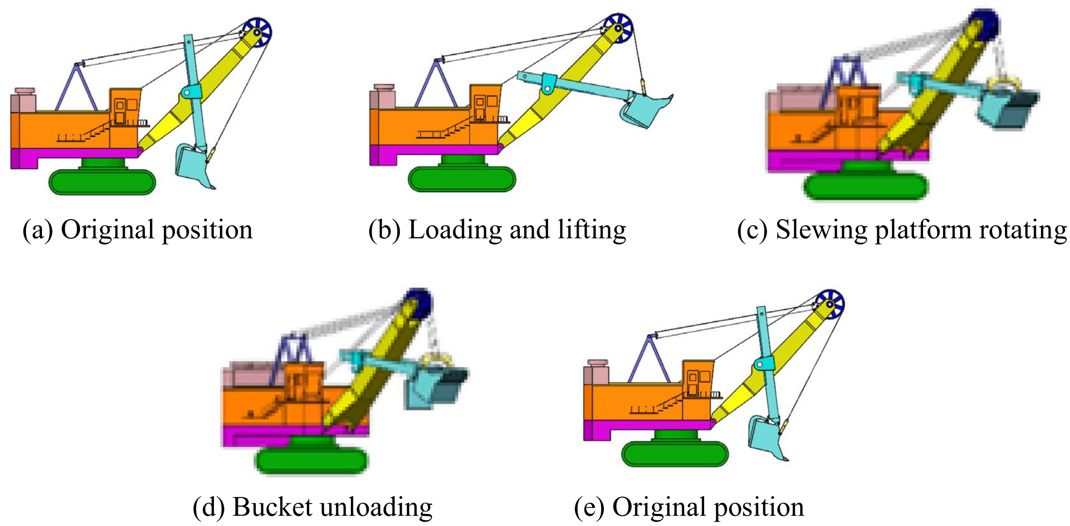


Figure 2 Operation process diagram of shovel

2 Working Principle

2.1 Shovel Working Principle

The shovel is mainly used to load the minerals and other materials after blasting into the mining dump truck. It is composed of a hoisting system, slewing system, tipping system, traveling system, and so on. Among them, the energy consumed and peak power required by the hoisting system and slewing system are the highest. In the hoisting system, the hoisting motor drives the drum, and the hoisting rope pulls the bucket up through the roller. In the slewing system, the slewing motor directly drives the upper slewing platform through the reducer to complete the rotation action. The main composition and the working principle of the hoisting and slewing system are shown in Figure 1.

The operation process of the shovel includes the following stages: loading and lifting, slewing platform rotating, bucket unloading and returning to the original position. Figure 2 shows the whole machine action diagram of the shovel in different operational stages. According to the working principle and process of the shovel, when the shovel is lifting after excavating minerals, the drum is driven to rotate by the hoisting motor. The hoisting device is lifted by the steel wire rope on the drum, and the bucket is driven by the pushing mechanism to extend and the shovelling depth will be adjusted. In this stage, the hoisting motor does external work and consumes electric energy. After lifting the hoisting device, the slewing platform is turned under the driving of the slewing motor. Then, the bucket filled with minerals is moved to the upper part of the hopper of the mining truck and unloaded the minerals into the truck. The slewing platform turns reversely to the excavation position after unloading minerals. When the hoisting device falls after rotating platform, the hoisting motor is driven by the gravity of the hoisting device to generate energy, and the bucket is driven by the pushing mechanism to retract and adjust the position so that the hoisting device can return to its initial posture and is ready to start the next excavation cycle.

The hoisting motor during the falling process of the hoisting device and the slewing motor during the decelerating process of the slewing platform are in the state of power generation. The generation energy is currently consumed through brake resistance, resulting a significant amount of energy waste. Moreover, the generated heat of the shovel driving system is also very serious, which further increase the cooling power of the driving system.

2.2 Hydraulic-Electric Hybrid System Working Principle

The working principle of the hoisting and slewing system of the novel hydraulic-electric hybrid driving shovel is depicted in Figure 3. The innovation of the proposed system is that the hydraulic pump/motor is added to the driving shaft of the original electric motor and the hydraulic accumulator is added to the original hydraulic system. In the system, the oil port of the hydraulic accumulator, the inlet of the overflow valve and the outlet of the hydraulic pump/motor are connected through a control valve, and the inlet of the hydraulic pump/motor and the outlet of the overflow valve are both connected to the oil tank. One end of the drive shaft of the hoisting motor is connected to the drum through the reducer, and the other end is connected to the hydraulic pump/motor. Similarly, one end of the drive shaft of the slewing motor

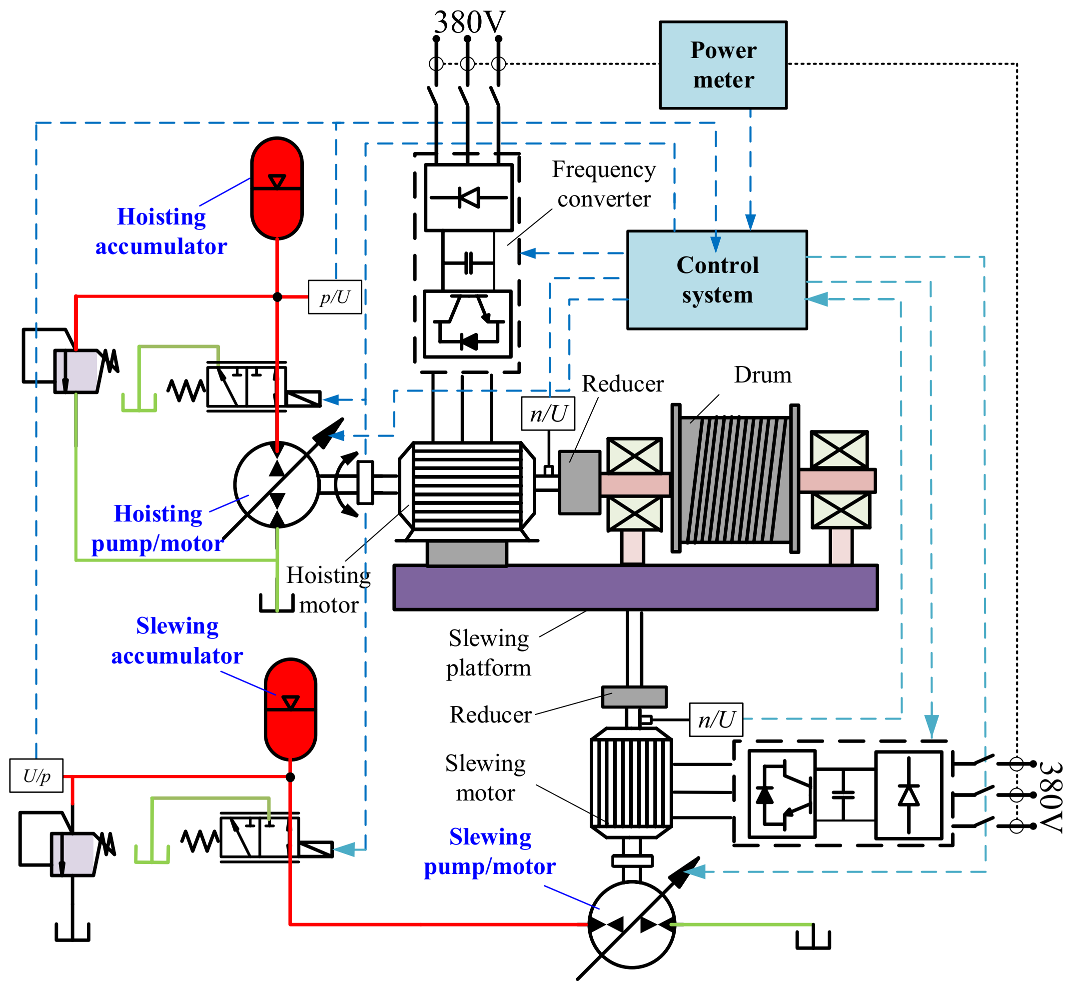


Figure 3 Working principle of hydraulic-electric hybrid drive lifting system of mining shovel

is connected to the slewing platform through the reducer, and the other end is connected with the hydraulic pump/motor.

The core components of the novel hydraulic-electric hybrid driving system are the hydraulic pump/motor and accumulator. Figure 4 illustrates the operating conditions of the core components. When the load of the driving system decelerates in the forward or reverse direction, the hydraulic pump/motor is in the "pump" working condition (II, IV). In this condition, the hydraulic pump is driven by the motor and pumps hydraulic oil into the accumulator. The gravitational and potential energy of the hoisting device or the kinetic energy of the slewing platform is recovered by the accumulator. When the load of the driving system accelerates in the forward or reverse direction, the hydraulic pump/motor is in the "motor" working condition (I, III). At this time, the accumulator releases the stored energy, and the high-pressure oil flows into the oil tank through the hydraulic motor to provide

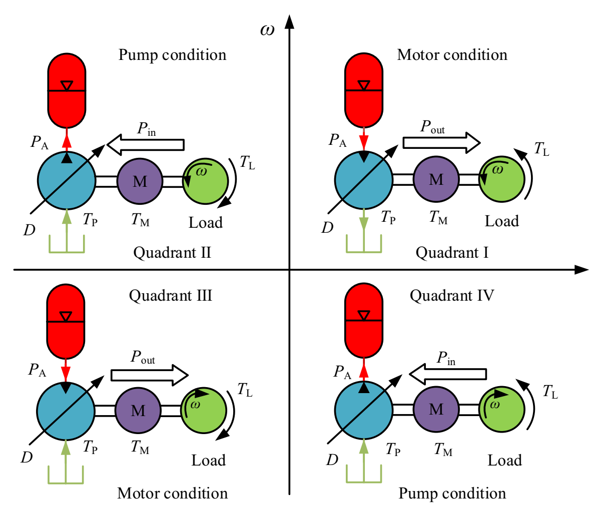


Figure 4 Operating conditions of hydraulic pump/motor

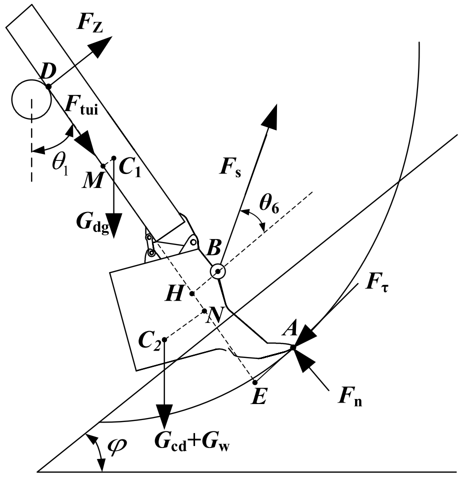


Figure 5 Force analysis of bucket rod and bucket assembly

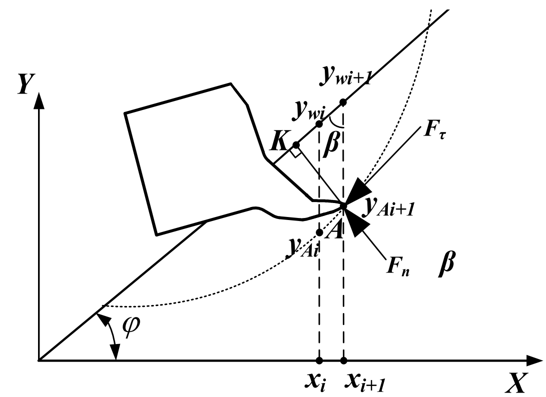


Figure 6 Analysis of excavation resistance

auxiliary torque for the hoisting or slewing motor, reducing the peak power of the motor. In the hoisting system, the initial output torque of the hydraulic pump/motor can be balanced with the torque generated by the self-weight of the shovel working device by setting the initial pressure of the accumulator. The hoisting motor only needs to maintain the movement of the working device and overcome the external load force.

In addition, considering the limitation of the installation space of the proposed system, the accumulator volume shall not be too large. That means that during the energy recovery process, the accumulator pressure may be higher than the set pressure of the overflow valve. At this time, the two-position three-way valve of the system works in the left position, and the proposed hydraulic system does not recover energy.

3 Theory Analysis

3.1 System Load Force Analysis

Figure 5 is the force analysis diagram of the handle-bucket assembly. The bucket assembly is mainly affected by various forces, including the digging resistance of the bucket tip F_τ and F_n, the gravity of the stick G_{dg} and the bucket G_{cd}, the gravity of the materials in the bucket G_w, the lifting force of the lifting rope to the stick F_Q, the pushing force F_{tui} of the crowd gear to the stick and the supporting force F_z.

According to the static equilibrium principle, take the moment of all external forces on the assembly to the instantaneous meshing point D of the handle and the crowd gear. The calculation formula is as follows:

$$\sum M_{\mathrm{D}}(F_{\mathrm{i}})=0. \tag{1}$$

By substituting each variable into Eq. (1), the lifting force can be calculated as follows:

$$\begin{aligned}F_{\mathrm{s}}=&[F_\tau l_{\mathrm{DE}}-F_{\tau\mathrm{n}}l_{\mathrm{AE}}-(G_{\mathrm{cd}}+G_{\mathrm{w}})\left(l_{\mathrm{C_2N}}\cos\theta_1-l_{\mathrm{DN}}\sin\theta_1\right)\\&+G_{\mathrm{dg}}\left(l_{\mathrm{DM}}\sin\theta_1+l_{\mathrm{C_1M}}\cos\theta_1\right)]/(l_{\mathrm{DH}}\cos\theta_2+l_{\mathrm{BH}}\sin\theta_2).\end{aligned} \tag{2}$$

The following formula can be obtained by projecting the force on the handle and bucket to the center line of the stick:

$$\sum F_{\mathrm{i}}=0. \tag{3}$$

The pushing force calculation formula can be obtained by taking each variable into Eq. (3):

$$F_{\mathrm{tui}}=F_{\mathrm{s}}\sin\theta_2+F_{\mathrm{n}}-(G_{\mathrm{dg}}+G_{\mathrm{cd}}+G_{\mathrm{w}})\cos\theta_1. \tag{4}$$

It can be seen from Eqs. (3) and (4), that the external load is included in the calculation process of lifting force and pushing force. And the external load mainly includes the gravity of minerals in the bucket and the digging resistance of the bucket tip. In order to simplify the calculation of the load, a mature empirical formula is used to calculate the digging resistance. The resistance is divided into tangential resistance F_τ and normal resistance F_n:

$$\begin{cases}F_\tau=\sigma_{\mathrm{w}}bC,\\F_{\mathrm{n}}=\psi F_\tau,\end{cases} \tag{5}$$

where, σ_w is the excavation resistance ratio; b is the bucket width; C is the cutting thickness; ψ is the proportionality coefficient.

The cutting thickness refers to the linear distance between the bucket tip and the mineral surface, as shown in Figure 6. The calculation method is as follows:

$$C=(y_{\mathrm{wi+1}}-y_{\mathrm{Ai+1}})\sin\phi=(y_{\mathrm{wi+1}}-y_{\mathrm{Ai+1}})\cos\alpha. \tag{6}$$

The calculation formula of mineral gravity in the bucket is as follows:

$$G_{\mathrm{wl}} = k\rho Sb, \tag{7}$$

where k is the ratio of the bucket actually loaded volume to the excavated mineral volume (0.9–0.93), ρ is the Mineral density; S is the swept area by the trajectory curve in the mineral stack; b is the bucket width.

As shown in Figure 6, when calculating the swept areas of the bucket tip trajectory curve, the trajectory can be divided into multiple straight lines, and the area of trajectory can be obtained by accumulating the area of the small quadrilateral $y_{\mathrm{wi+1}}$, y_{wi}, y_{Ai}, $y_{\mathrm{Ai+1}}$ formed by each straight line:

$$S = \sum \frac{(y_{\mathrm{wi+1}} - y_{\mathrm{Ai+1}}) + (y_{\mathrm{wi}} - y_{\mathrm{Ai}})}{2}(X_{\mathrm{i+1}} - X_{\mathrm{i}}). \tag{8}$$

The required energy of the shovel hoisting device in the lifting process is as follows:

$$E_{\mathrm{s}} = \int F_{\mathrm{s}} v_{\mathrm{Q}} \mathrm{d}t. \tag{9}$$

3.2 Energy Efficiency Analysis

The frequency converter is adopted to drive the hoisting and slewing motors. It is assumed that the electric efficiency of the motor is η_1 and the power generation efficiency is η_2. Taking the motor in the hoisting device as an example, when the bucket is lifting and falling (when the slewing is accelerating or decelerating) the electric energy consumed and produced by the motor is respectively as follows:

$$E_{\mathrm{e1}} = \frac{E_{\mathrm{s1}}}{\eta_1} = \frac{\int T_{\mathrm{e}}\omega_{\mathrm{lift}}\mathrm{d}t}{\eta_1}, \tag{10}$$

$$E_{\mathrm{e2}} = \frac{E_{\mathrm{s2}}}{\eta_2} = \frac{\int T_{\mathrm{e}}\omega_{\mathrm{fall}}\mathrm{d}t}{\eta_2}, \tag{11}$$

where E_{e1} is electric energy consumed by hoisting motor; E_{e2} is electric energy produced by hoisting motor; E_{s1} is required energy in the lifting process; E_{s2} is required energy in the falling process; T_{e} is load torque of hoisting motor; ω_{i} is the speed of the motor (i=lift, fall):

$$P_{\mathrm{average}} = \frac{E_{\mathrm{s1}}}{\eta_1 t_{\mathrm{lift}}}, \tag{12}$$

$$P_{\mathrm{max}} = \frac{\max(F_{\mathrm{s}} v_{\mathrm{Q}})}{\eta_1}. \tag{13}$$

To facilitate the analysis, the leakage of the hydraulic system and the efficiency of the hydraulic pump/motor are ignored. The stored energy of the accumulator during the falling process of the hoisting device is as follows:

$$\sum M_{\mathrm{D}}(F_{\mathrm{i}}) = 0, \tag{14}$$

where E_{e3} is the output energy of the motor during the falling process of handle and bucket.

When the hoisting device lifting, the accumulator releases the energy. The hoisting device is jointly driven by hydraulic pump/motor and hoisting motor. The electric energy consumed E'_{e1} and instantaneous power P' of the hoisting motor are respectively as follows:

$$E'_{\mathrm{e1}} = \frac{E_{\mathrm{s1}} - E_{\mathrm{p}}}{\eta_1} = \frac{E_{\mathrm{s1}} - E_{\mathrm{e3}} - E_{\mathrm{s2}}}{\eta_1}, \tag{15}$$

$$P' = \frac{F_{\mathrm{s}} v_{\mathrm{Q}} - P_{\mathrm{pump/motor}}}{\eta_1}, \tag{16}$$

where $P_{\mathrm{pump/motor}}$ is the power of hydraulic pump/ motor.

The total electric energy consumed by the hoisting motor in one lifting and falling cycle of the hoisting device is as follows:

$$E'_{\mathrm{etotal}} = \frac{E_{\mathrm{e3}}}{\eta_1} + \frac{E_{\mathrm{s1}} - E_{\mathrm{e3}} - E_{\mathrm{s2}}}{\eta_1} = \frac{E_{\mathrm{s1}} - E_{\mathrm{s2}}}{\eta_1}. \tag{17}$$

During the lifting processes of the hoisting device, the average power and peak power of the hoisting motor are as follow respectively:

$$P'_{\mathrm{average}} = \frac{E_{\mathrm{s1}} - E_{\mathrm{e2}} - E_{\mathrm{s3}}}{t_{\mathrm{lift}}}, \tag{18}$$

$$P'_{\mathrm{max}} = \frac{\max(F_{\mathrm{s}} v_{\mathrm{Q}} - P_{\mathrm{pump/motor}})}{\eta_1}. \tag{19}$$

By comparing Eqs. (10), (13), (15), (17) and (19), it can be concluded that:

$$P'_{\mathrm{max}} < P_{\mathrm{max}}, \tag{20}$$

$$E'_{\mathrm{e1}} < E_{\mathrm{e1}}, \tag{21}$$

$$E'_{\mathrm{etotal}} = \frac{E_{\mathrm{s1}} - E_{\mathrm{s2}}}{\eta_1} < \frac{E_{\mathrm{s1}}}{\eta_1}. \tag{22}$$

It can be seen from the theoretical analysis that, compared with the hoisting device of the purely electric driving shovel, the energy consumption and peak power of the hoisting motor of hydraulic-electric hybrid drive shovel are effectively reduced.

4 System Feasibility Validation

Because of the large volume and mass of the mining shovel, if the novel principle verification test is directly carried out on the shovel, the cost is high and the difficulty is very large. A test prototype of the hydraulic-electric hybrid drive system can be constructed on a small test platform to verify the feasibility and effectiveness of the proposed system. Then on this basis, by constructing the multidisciplinary whole-machine co-simulation model based on the real physical model. This model elucidates the working and energy consumption characteristics of the proposed system within the shovel, providing a solid foundation for further test and promotion. According to the working principle of the proposed system and the working characteristics of the shovel hoisting device, a small test prototype of the proposed system is constructed in the elevator lifting platform. The main motor of the elevator is auxiliary driven by a hydraulic pump/motor, and the gravity potential energy of the elevator is recycled through the accumulator. The working principle and physical diagram of the constructed smell test prototype are shown in Figure 7. The small test prototype is installed in a real building environment, and the operation and energy-saving characteristics of the novel hydraulic-electric hybrid drive elevator under multi-load conditions are studied.

The test results of the lifting and falling processes of a hydraulic-electric hybrid drive elevator with a 900 kg load are shown in Figure 8. It can be seen from the figure that the peak power of the elevator motor can be reduced from 19.1 kW to 14.8 kW (reduced by 22.5%) with the assistance of the accumulator and hydraulic pump/motor. The test system is loaded with 100 kg, 300 kg, 700 kg and 900 kg weights respectively, and the lifting and falling tests are carried out. The motor energy consumption data under various load conditions are shown in Table 1. According to table, the adoption of the novel system can reduce motor energy consumption by an average of 12%.

It can be seen from Figure 8 and Table 1 that the test platform runs well under different loads and has an obvious energy-saving effect. If the proposed system is further applied to the shovel, and the proposed system is adopted in the lifting system and slewing system of the shovel, a more significant energy-saving effect can be achieved.

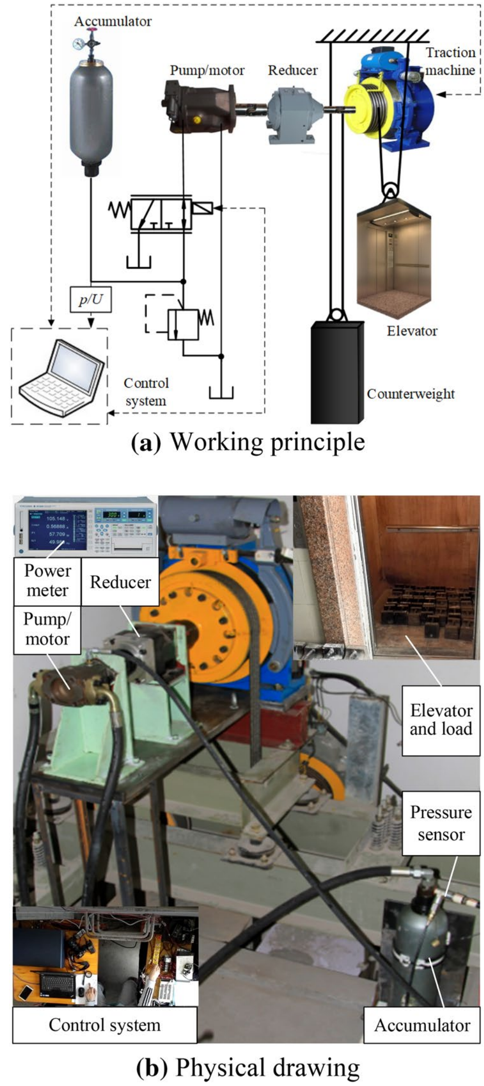


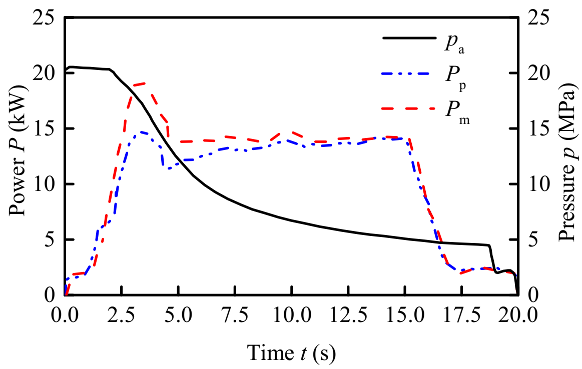
Figure 7 Hydraulic-electric hybrid drive elevator verification system test platform

5 Co-simulation Model

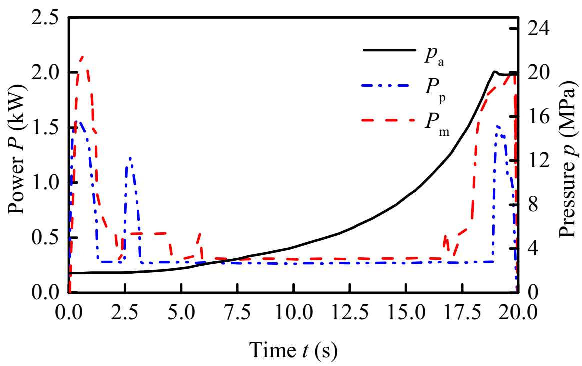
5.1 Model Building

The hydraulic-electric hybrid driving principle was verified by the previous test platform. However, unlike the actual shovel hoisting device, the load changes during the shovel lifting and falling process. In order to make the research results more convincing, the mechanical-electric-hydraulic joint simulation model of the hoisting and slewing system of the hydraulic-electric hybrid drive shovel system is established based on the mature digital prototype modelling principles and methods of the research team (this method has been verified by many prototypes with different specifications [17, 18, 25–28]). Then, the lifting, falling and rotating process of the shovel are simulated.

In the early stage of the research, aiming at the operation and energy consumption characteristics of hydraulic excavators, the theory and method of digital prototype modelling have been studied. The digital prototypes of 6 t, 20 t, and 76 t hydraulic excavators were built, respectively. The 6 t meter in and meter out



(a) Load 900 kg lifting condition



(b) Load 900 kg falling condition

Figure 8 Hydraulic-electric hybrid drive elevator test result (Where p_a is the accumulator pressure; P_p is the motor power of the purely electric drive hoisting system; P is the motor power of the hydraulic-electric hybrid drive hoisting system)

Table 1 Energy consumption

m_i (kg)	E_{lo} (kJ)	E_{lh} (kJ)	η_l (%)
100	133.44	115.4	13.52
300	101	86.8	14.06
700	157.6	140.4	10.91
900	231.2	208.2	9.95

independently controlled hydraulic excavator and 76 t energy-saving hydraulic excavator test prototypes were then developed successfully [25–28]. Referring to the mature digital prototype modelling experience accumulated by the research team, the co-simulation model of the hydraulic-electric hybrid drive shovel hoisting and slewing system shown in Figure 9 is constructed. Firstly, a multi-body dynamic mechanical model which can reflect the real physical structure and operation characteristics of the shovel is constructed. Then, according to the obtained parameters, the models of each electric motor and its AC variable frequency control system are established. On this basis, the hydraulic pump/motor, accumulator and its corresponding control valve are added to form the hydraulic-electric hybrid driving system. Finally, the hydraulic pump/motor is coaxially connected with the electric motor of the mining shovel, and then the co-simulation model of the mechanical-electric-hydraulic hybrid drive shovel hoisting and slewing system is formed. The main performance parameters of the shovel are shown in Table 2. The parameters of key hydraulic components of the proposed system are shown in Table 3.

5.2 Analysis of Simulation Results

The following working conditions are simulated and analyzed by using the co-simulation model of the hydraulic-electric hybrid drive shovel. First, the process of empty bucket falling and full load lifting of the hydraulic-electric hybrid drive hoisting system is simulated and analyzed to clarify the working and energy consumption characteristics of the hoisting system. The specific workflow is from (a) position to (b) position in Figure 2, and then back to (a) position. Secondly, the rotation process of the hydraulic-electric hybrid drive slewing system is analyzed to clarify the working and energy consumption characteristics of the slewing system. The specific workflow is from (b) position to (c) position in Figure 2, and then back to (b) position. Finally, the influence of hydraulic accumulator parameters on the working and energy consumption characteristics of hoisting and slewing systems is analyzed. In the simulation processes, the vehicle-mineral distance is set as 4 m, the mineral is set as coal and the mineral inclination angle is set as 35°.

Figure 10 shows the accumulator pressure curve and compares the hoisting motor power between the purely electric drive shovel and the novel hydraulic-electric hybrid drive shovel during the falling and lifting process of the hoisting device.

It can be seen from Figure 10 that in the falling process, the hoisting motor of the purely electric drive shovel system is in the power generation state, with the maximum generated power of 262 kW, and the generated energy in this process is 1074 kJ. As for the hydraulic-electric hybrid drive shovel, because the hydraulic pump/motor connected with the hoisting motor always provides the load torque for the motor, the hoisting motor is always in the motoring condition during this process. And due to the load torque, the hoisting device cannot be felled normally only by the gravity of the stick and bucket. Additional output power generated by the hoisting motor is required to achieve torque balance between the hydraulic pump/motor and the hoist drum so that the hoisting

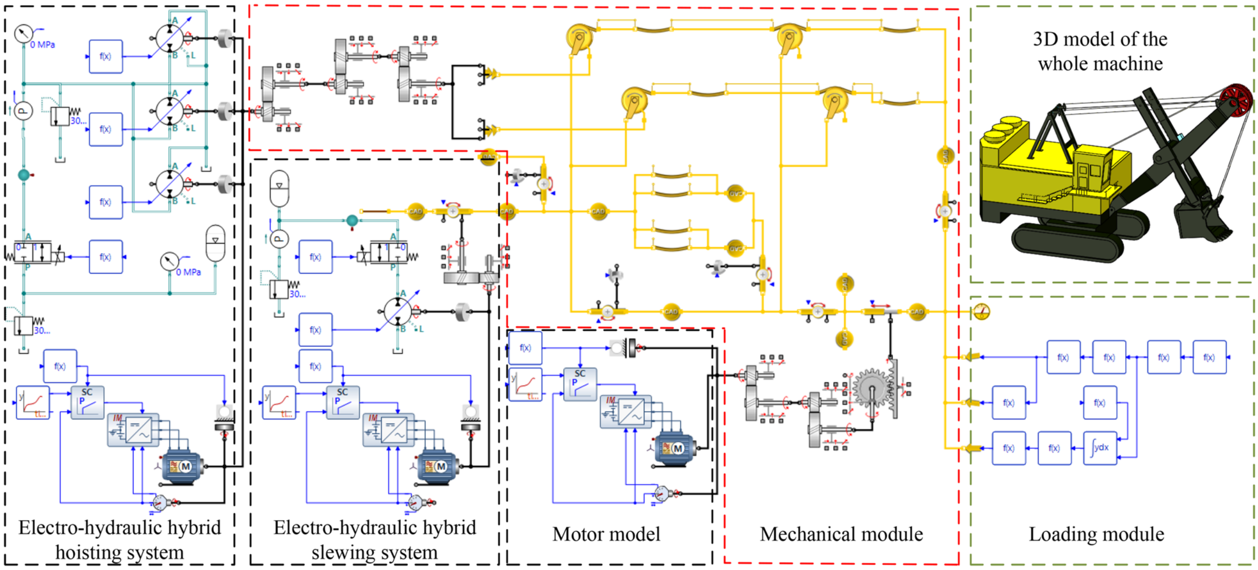


Figure 9 Co-simulation model of the hydraulic-electric hybrid drive shovel hoisting and slewing system (ESI SimulationX: The software integrates mathematical models from multiple disciplines such as mechanical, hydraulic, control. The mathematical models are packaged and integrated through graphical modules and interfaces. The software can realize the direct and real-time interaction of mechanical and hydraulic system information without exchanging data with other simulation software through the interface, avoiding the error brought by data exchange and improving the accuracy and efficiency of simulation)

Table 2 Main performance parameters of the shovel

Name	Value	Name	Value
Standard bucket capacity (m^3)	12	Nominal push speed (m/s)	0.65
Bucket capacity range (m^3)	10–18	Lifting motor power (kW)	560
Maximum lifting force (kN)	1039	Pushing motor power (kW)	2 × 130
Maximum pushing force (kN)	637	Slewing motor power (kW)	2 × 130
Nominal lifting speed (m/s)	1	Theoretical pro-ductivity (m^3/h)	1490

Table 3 The parameters of key components of the system

System	Components	Parameter
Hoisting system	Hydraulic pump/motor	Displacement 1000 mL/r
	Accumulator	Volume 600 L,
	Pre-charge pressure	21.8 MPa
Slewing system	Hydraulic pump/motor	Displacement 600 mL/r
	Accumulator	Volume 350 L
	Pre-charge pressure	28 MPa

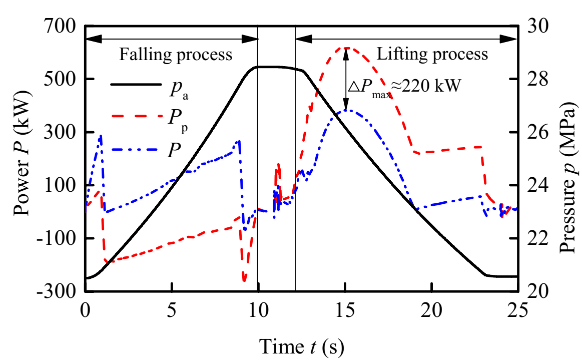


Figure 10 Power of hoisting motor and pressure of accumulator

motor produces a peak electric power of 300 kW in the process. The gravity potential energy of the hoisting device and the output energy of the hoisting motor are converted into the pressure energy of the accumulator through the hydraulic pump/motor, and the oil pressure in the accumulator rises from 20.5 MPa to 28.5 MPa.

In the lifting process, the peak power of the hoisting motor of the purely electric drive shovel is 600 kW. As for the novel hydraulic-electric hybrid drive shovel, the drum of the shovel is driven by the hydraulic pump/motor (driven by the accumulator) and hoisting motor together, and the peak power of the hoisting motor is about 380 kW. Compared with the purely electric drive shovel system, the peak power can be reduced by 36.7%. The pressure of the accumulator decreases from 28.5 MPa to 20.5 MPa. According to the integral calculation of the power curve of the hoisting motor, the electric energy consumed by the motor in one lifting and falling cycle of the shovel hoisting device can be obtained. The energy consumed by the motor in the purely electric driving shovel hoisting device is 4332 kJ, while the energy consumed by the motor in the hydraulic-electric hybrid drive shovel hoisting device is only 3048 kJ, which can save 29.6% of the energy consumption.

Figure 11 illustrates the pressure curve of the accumulator and the comparison curve of slewing motor power between the purely electric drive shovel and the novel hydraulic-electric hybrid drive shovel during the accelerating and decelerating process of the slewing platform.

It can be seen from Figure 11 that the initial oil pressure of the accumulator is 28 MPa. When the rotating speed of the slewing platform accelerates, the accumulator releases high-pressure oil, and its pressure decreases from 28 MPa to 26.3 MPa. When the rotating speed of the slewing platform decreases, the hydraulic pump/motor is driven by the inertia of the slewing platform, and then the low-pressure oil in the hydraulic oil tank is pumped into the accumulator, and the oil pressure of the accumulator be restored from 26.3 MPa to 28 MPa. Compared with the purely electric driving shovel system, the peak power of the slewing motor is only 45 kW (reduced by 300 kW). In a rotating cycle of the slewing platform, the energy consumption of the slewing motor is only 157 kJ (reduced by more than 59.4%).

The electro-hydraulic hybrid drive system can reduce energy consumption by 1514 kJ in a single working condition. If the system works for 20 hours a day, with a single working cycle of 30 s, it can save 909 kWh of electricity per day, and if it works for 300 days a year, it can save about RMB 300000 in electricity cost.

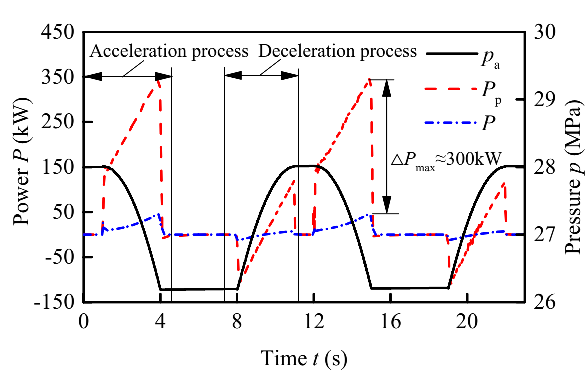


Figure 11 Power comparison of slewing motor

6 Influence of Accumulator

6.1 Influence of Hoisting Device

6.1.1 Accumulator Initial Pressure

To study the effect of the initial oil pressure of the accumulator on the energy efficiency of the hoisting device of the novel hydraulic-electric hybrid driving shovel, the lifting and falling process of the shovel hoisting device with initial oil pressure in the accumulator of 19 MPa, 20 MPa, 21 MPa, and 22 MPa were simulated and analyzed. The accumulator volume is set as 650 L.

Figure 12 illustrates the curves of the hoisting motor power under different initial pressures in the accumulator. It can be seen that in the falling process of the hoisting device, to ensure normal falling and balance the torque between the hydraulic pump/motor and the drum, the higher the initial pressure of the accumulator is, the higher the output power of the hoisting motor will be. In the lifting process of the hoisting device, the hoisting device is driven together by the accumulator

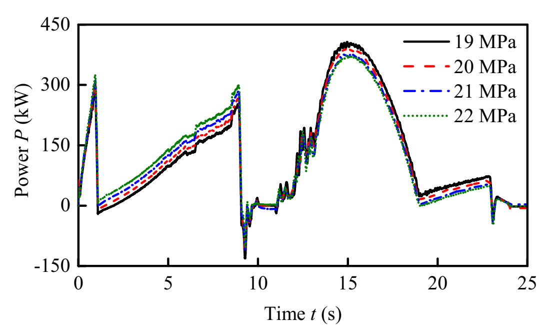


Figure 12 Power of hoisting motor

Table 4 Energy consumption of the hoisting motor at different initial oil pressures of the accumulator

p (MPa)	P_{max} (kW)	η_3(%)	E (kJ)	η_4(%)
19	407	32.2	3058	29.4
20	391	34.8	3036	29.9
21	379	36.8	3024	30.0
22	373	37.8	3084	28.8

and the motor. When lifting the same minerals, the higher the initial pressure of the accumulator, the greater the reduction of the peak power of the hoisting motor.

Table 4 shows the power consumption index of the hoisting motor in a lifting cycle of the hoisting system when the initial oil pressure of the accumulator is different.

In Table 4, η_3 is the ratio of peak power reduction:

$$\eta_3 = \frac{P_{\max} - P'_{\max}}{P_{\max}}, \tag{23}$$

η_4 is the ratio of energy consumption reduction:

$$\eta_4 = \frac{E_{e1} - E'_{e1}}{E_{e1}}. \tag{24}$$

It can be seen from the table that with the increase of the initial pressure of the accumulator, the peak power of the hoisting motor decreases gradually, and the ratio of peak power reduction η_3 increases gradually. When the initial pressure of the accumulator is 19 MPa, 20 MPa, and 21 MPa respectively, the higher the initial pressure of the accumulator is, the higher the energy saving ratio η_4 is. However, when the pressure in the accumulator is 22 MPa, it reaches the overflow pressure of the safety valve during the falling process of the hoisting device, and the energy recovery function does not work. The potential energy of the hoisting device is still dissipated through heat energy, and the energy saving ratio η_4 is reduced.

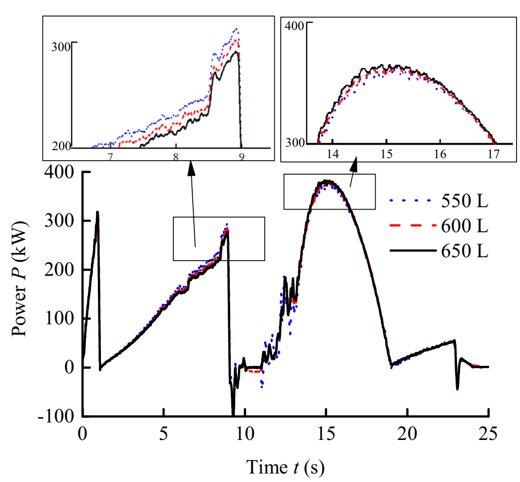


Figure 13 Power of hoisting motor

6.1.2 Accumulator Volume

To study the effect of accumulator volume on the energy efficiency of the novel hydraulic-electric hybrid drive shovel hoisting device, the lifting process and falling process of the hoisting device with accumulator volumes of 550 L, 600 L, and 650 L were simulated and analyzed. The initial pressure of the accumulator is set as 21 MPa.

Figure 13 illustrates the curves of hoisting motor power under different accumulator volumes. According to the figures, when the initial pressure of the accumulator is 21 MPa, the smaller the accumulator volume is, the greater the reduction of peak power of the hoisting motor is. The energy consumption of the lifting motor in the process can be obtained by integrating the power curve of the motor.

Table 5 shows the power consumption index of the hoisting motor in one lifting and falling cycle of the hoisting system when the accumulator volume is different. It can be seen from the table that when the accumulator volume is different, there is little difference in energy saving effect.

6.2 Influence of Slewing Platform

6.2.1 Accumulator Initial Pressure

In order to study the effect of the initial pressure of the accumulator on the energy efficiency of the slewing platform of the hydraulic-electric hybrid driving shovel, the acceleration and deceleration process of the slewing platform of the shovel with accumulator initial pressure

Table 5 Energy consumption of the hoisting motor at the different volume of the accumulator

V (L)	P_{max} (kW)	η_3(%)	*E* (kJ)	η_4(%)
650	382	36.3	3030	30.1
600	379	36.8	3024	30.0
550	375	37.5	3049	29.6

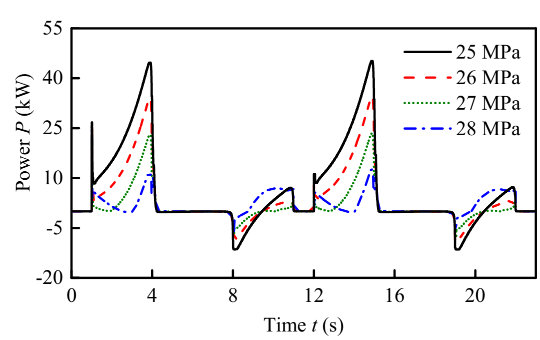


Figure 14 Power of slewing motor

Table 6 Energy consumption index of the slewing motor at a different initial pressure of the accumulator

p (MPa)	P_{max} (kW)	η_3(%)	*E* (kJ)	η_4(%)
25	45	57.35	157	59.4
26	34	59.47	100	61.8
27	23.4	61.51	47.3	63.9
28	12.6	63.56	47.4	63.9

Table 7 Power and energy consumption index of the slewing motor at the different volumes of the accumulator

V (L)	P_{max} (kW)	η_3(%)	*E* (kJ)	η_4(%)
350	12.6	63.91	47.4	63.9
400	11.9	64.33	40.5	64.3
450	11.4	64.37	39.8	64.4
500	10.9	64.45	37.6	64.4

of 25 MPa, 26 MPa, 27 MPa, and 28 MPa are simulated and analyzed. The accumulator volume is set as 350 L. Figure 14 show the slewing motor power curves under the different initial pressure of the accumulator.

Table 6 shows the peak power and index of energy consumption of the slewing motor. It can be seen from the table and figure that in the rotating process of the slewing platform, the higher the initial pressure is, the lower the peak power of the slewing motor is. With the increase of the initial oil pressure of the accumulator, the energy consumption of the slewing motor is lower.

6.2.2 Accumulator Volume

To investigate the effect of accumulator volume on the energy efficiency of the novel hydraulic-electric hybrid drive shovel slewing platform, the acceleration and deceleration process of the shovel slewing platform with accumulator volumes of 350 L, 400 L, 450 L, and 500 L were simulated and analysed. The initial pressure of the accumulator is set as 28 MPa.

Figure 15 illustrates the slewing motor power curve under different accumulator volumes. Table 7 shows the power and energy consumption index of the slewing motor at the different volumes of the accumulator. It can be seen from the figure and table that, the larger the volume of the hydraulic accumulator is, the smaller the peak power of the slewing motor is. With the increase of accumulator volume, the electric energy consumption of the slewing motor decreases gradually. However, the larger the volume, the more costly it will be, and the more difficult it will be to realize the reasonable layout of the slewing platform of the shovel. Therefore, the accumulator volume should not be too large.

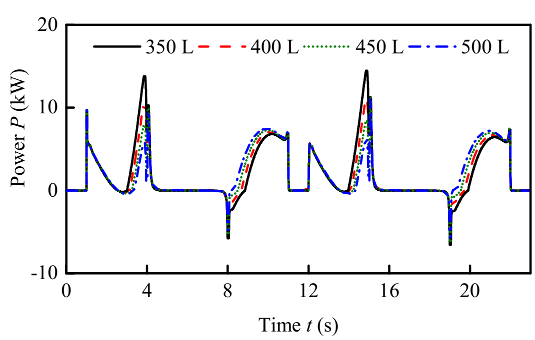


Figure 15 Power of slewing motor

7 Conclusions

This paper presents a novel hydraulic-electric hybrid drive principle for shovel hoisting and slewing system, capable recycling the gravitational potential energy of the hoisting device and the kinetic energy of the slewing platform by adding hydraulic pumps/motors and accumulators. Both the installed power, peak power, and energy consumption of the driving motor can be reduced. Through experiment and simulation research, the following conclusions can be obtained.

(1) The feasibility of the novel hydraulic-electric hybrid driving system is verified by the principle test platform. The results show that, with the proposed hybrid driving system, the energy consumption of the electric motor can be reduced by 12%.
(2) The co-simulation model of the shovel is established to analyze the operational and energy efficiency characteristics of the hoisting and slewing system featuring the hydraulic-electric hybrid driving system. The results show that, adopting the proposed system, compared with the traditional purely electric driving shovel system, the peak power of the hoisting motor can be reduced by 36.7%, and the energy consumption can be reduced by 29.7%. Furthermore, the peak power and the energy consumption of slewing motor are decreased by 86.9% and 59.4%, respectively.
(3) The influence of accumulator parameters on the energy efficiency of the hydraulic-electric hybrid driving system is analyzed. The results show that the accumulator volume has minor effect on the peak power and energy consumption of the electric motor. In contrast, the initial oil pressure of the accumulator significantly influences the peak power and energy consumption of the electric motor. The remarkable energy-saving effect can be obtained by

optimizing the accumulator volume and initial oil pressure.

The proposed system can be widely used in heavy hoisting and slewing equipment driven by the electric motor.

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Authors' Contributions
XW was in charge of the whole trial and wrote the manuscript; LQ guided the writing of the manuscript. LG and YL assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

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Availability of Data and Materials
The datasets supporting the conclusions of this article are included within the article.

Declarations

Ethics approval and Consent to Participate
Not applicable.

Consent for Publication
Not applicable.

Competing Interests
The authors declare no competing financial interests.

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