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Energy Saving Characteristics of a Winch System Driven by a Four-Quadrant Hydraulic Pump

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Abstract: In this study, an integrated system of winch driving and potential energy recovery using a four-quadrant pump was proposed, aimed at the large amount of recoverable gravitational potential energy in a winch system. The proposed system changed the original open system into a closed-structure part, using a four-quadrant pump to drive the winch, and an open-structure part, using an open hydraulic pump to balance torque. The closed-structure and open-structure parts were coaxial, and connected with the engine through the transfer case, which was able to make full use of the four-quadrant pump characteristics. It was able to achieve flow regeneration when the weight was lowered, and to achieve direct use of gravitational potential energy. The AMESim model of the original and proposed systems was further established according to a working characteristics analysis of the energy consumption of the winch-driving system. The simulation results verified that the proposed system kept good controllability while recovering potential energy. An experimental prototype was built; the test results showed that, compared with the original winch system, the proposed system increased lifting speed and reduced fuel consumption significantly. Additionally, diesel consumption was reduced by 87% in the descending process.

Keywords: winch system; energy saving; four-quadrant hydraulic pump; hydraulic energy storage; balance torque

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1. Introduction

Around the world, the industrial sector uses more energy than any other end-use sector. Currently, this sector is consuming about 37% of the world's total delivered energy [1]. Construction machinery is an indispensable part of industrial development. Among their variety, there is a wide range of lifting devices which consume significant energy during repeated operation. As such, there is also significant recoverable potential energy when these devices are in the process of descending. The effort to recover the gravitational potential energy in the descending process and effectively reduce the energy consumption of lifting systems has become an important direction in research [2].

According to their driving elements, lifting systems can be divided into hydraulic cylinder drives and hydraulic motor drives. Lifting systems using hydraulic cylinder drives are mostly used in hydraulic excavators, loaders, forklifts, and other construction machinery. Research on energy saving in lifting systems using hydraulic cylinder drives began some time ago, and there are many related studies in the literature. As of the present, most research has focused on energy recovery, which can be divided into electrical, hydraulic, and mechanical methods. Electrical energy recovery refers to storing the recovered electric energy into a super-capacitor or battery. Electric energy is produced when the potential energy is used to drive the hydraulic motor and generator [3–5]. When an all-electric drive is used, it can achieve green energy saving, but the energy recovery and reuse process requires multiple conversions. Hydraulic energy recovery has been shown to directly recover gravitational potential energy and store it in hydraulic accumulators [5,6]. Hydraulic energy recovery can also be realized by adding a hydraulic accumulator in a closed pump-controlled differential hydraulic cylinder circuit in which energy reuse is realized through coupling with the main hydraulic pump torque [7]. The energy recovery and reuse of differential hydraulic cylinders can be realized through an asymmetric single pump [8,9]. When the energy storage hydraulic cylinder [10,11] or energy storage chamber [12–14] is used to recover the gravitational potential energy, the gravity of the working device can also be balanced to achieve the recovery and reuse of the gravitational potential energy. Hydraulic energy recovery reduces the intermediate conversion and is more suitable for heavy-duty conditions. For a limited installation space, Quan et al. proposed a liquid–gas energy storage drive with a three-chamber hydraulic cylinder, integrated with energy storage and drive to minimize space requirements [15]. Mechanical energy recovery utilizes a rotating flywheel to store energy [16]; these can respond quickly due to their high energy density.

Cranes, rotary drilling rigs, and other construction machinery which need long-distance vertical transport operation are limited by the effective stroke and maximum working pressure of the hydraulic cylinder due to their height and weight. Under such conditions, a hydraulic motor is utilized to lift the load. Research into energy-saving methods in lifting systems driven by hydraulic motors has focused on two aspects: the performance of balance valves in traditional hydraulic systems and different energy recovery methods. The lifting weight in a hydraulic motor drive system is large, as is the lifting vertical distance. Thus, the requirements for its control and energy saving are high. Most traditional hydraulic systems use the open system. In the descending process, the balance valve is needed to achieve stable descent of the weight, and the gravitational potential energy is converted into heat and dissipated in the hydraulic oil. According to the characteristics of different working conditions of construction machinery, research has focused on the optimization of the balance valve and the control system [17–19], factors affecting the balance valve in the dynamic analysis [20,21], and energy-saving methods applicable throughout the whole machine. Some researchers have verified the energy-saving effects of energy recovery through simulation and experiments. He et al. proposed an electric recovery system based on a winch-motor-synchronous motor and studied the economic point of recovery efficiency through experimental research [22]. Zhu and Fang et al. verified the feasibility and energy-saving potential of a proposed scheme, which applied hydraulic and electrical energy recovery to recover the potential energy of a rotary drilling rig's main winch through simulation [23,24]. Wu used the energy recovery system of a pump/motor with secondary regulation and an accumulator to realize the recovery of gravitational potential energy during winch descent [25].

A four-quadrant pump can work in all four quadrants. In the first and third quadrants, it works in hydraulic motor mode. While in the second and fourth quadrants, it works in hydraulic pump mode. A four-quadrant pump can simplify a system and is widely used in energy-saving efforts. Achten developed a four-quadrant hydraulic transformer to reduce throttling losses through valves [26]. A four-quadrant pump was also used in a closed-circuit configuration of a skid-steer loader, offering energy savings by eliminating hydraulic losses and allowing energy recovery [27]. Huang proposed an electro-hydrostatic actuator (EHA) with four-quadrant energy regulation based on a hydraulic scheme. He discussed the principle, structure design, and control strategy to improve the efficiency of the system [28]. The application of four-quadrant pumps in a hydraulic system has been increasing, especially when there is a need for energy recovery.

Winch systems are often used in construction machinery that perform long-distance and high-load operations. Their lifting systems are driven by hydraulic motors. Currently, most research on energy-saving methods for winch systems has applied different ways to recover energy and they all need additional energy recovery devices. In view of the fact that the four-quadrant pump can work in four quadrants, a winch lifting system based on the four-quadrant pump which can realize the energy storage and drive is proposed.

The proposed winch driving structure with a four-quadrant pump can eliminate the whole machine's assembly problem, reducing the energy loss during the energy transfer and conversion process. Moreover, combined with the open system, the proposed system can ensure the stability of the system, keep the winch down quickly, and further improve work efficiency. The parameter difference between the original open system and the proposed winch system with energy-saving are analyzed. The test prototype is set up. Additionally, winch operation characteristics and recovery efficiency of the original open system and the proposed winch system with energy-saving under different engine speeds and different load masses are tested.

2. System Working Principle

The proposed winch system with energy-saving is shown in Figure 1. The energy storage cavity is integrated into the four-quadrant pump/motor, which is used to substitute the commonly used variable displacement pump. A close-structure part consisting of a four-quadrant variable pump/motor and winch motor is used to replace the commonly used open hydraulic system. The close-structure part is used to directly recover and reutilize the gravitational potential energy. While there is excess negative power after the four-quadrant pump/motor, absorbing the winch drag torque will lead to reversing drag overspeed. Therefore, a balance of the control open-structure part with the open-type variable displacement pump, which is a coaxial transmission with the four-quadrant pump/motor, is designed. An open-type variable pump balances the energy storage principle and, through setting an appropriate displacement, is adopted in the system, which can balance the excess winch drag torque and eliminate the influence of the hydraulic energy storage units on the winch lifting system and the whole vehicle. When it is necessary to reduce the absorption of negative power in the open-structure part, the displacement of the open-type variable pump in the open control system is reduced to decrease the oil supply to the pump. When the winch rises, the open-type pump absorbs oil from the tank and the output torque is transmitted to the four-quadrant pump/motor through a transfer case, which can reduce the engine output torque. Combined with the accumulator control valves, the open-structure part can also absorb the excess potential energy during the winch descending process and releases the recovered hydraulic energy during the winch lifting process.

The force balance equation of the winch motor in the descending process can be expressed as

$$p_L D_m = (p_1 - p_2) D_m = J_m \dot{\omega}_m + B_m \omega_m + T_L \tag{1}$$

where, J_m is the total inertia moment of the winch motor and load. B_m is the viscous damping coefficient. ω_m is the actual speed of the winch motor. T_L is the external load torque transferred to the winch motor by a heavy load. D_m is the displacement of the winch motor. p_1 and p_2 are pressure at both ends of the winch motor, respectively. p_L is the load pressure of the winch motor.

In Equation (1), the external load torque transferred to the winch motor by heavy load accounts for the largest proportion. During the working process, the energy consumed to overcome the weight of gravity also accounts for a large proportion. Using the hydraulic balance energy storage principle of the four-quadrant pump/motor, and by setting the appropriate displacement of the four-quadrant pump/motor, which can work in pump or motor mode, the drag torque that the weight loaded on the winch motor can be mostly balanced by the four-quadrant pump/motor. Meanwhile, the excess drag torque is balanced by the open-structure part which is the coaxial transmission with the four-quadrant pump/motor through the transfer case. Namely

$$\frac{p_c D_c}{\eta_v} + \frac{p_o D_o}{\eta_m} = p_L D_m \tag{2}$$

where, p_c and p_o are the hydraulic pump load pressure of the close-structure part and the open-structure part, respectively. D_c and D_o are the hydraulic pump displacement of the close-structure part and the open-structure part, respectively. η_v and η_m are the volume efficiency and the mechanical efficiency, respectively.

According to Equation (2), Equation (1) can be simplified and obtained as

$$\frac{p_c D_c}{\eta_v} = J_m \dot{\omega}_m + B_m \omega_m + T_L - \frac{p_o D_o}{\eta_m} \tag{3}$$

According to Equation (3), after the adoption of hydraulic energy storage and driving system, the four-quadrant pump/motor can realize the weight potential energy recovery. The energy consumption of the driving system can be greatly reduced.

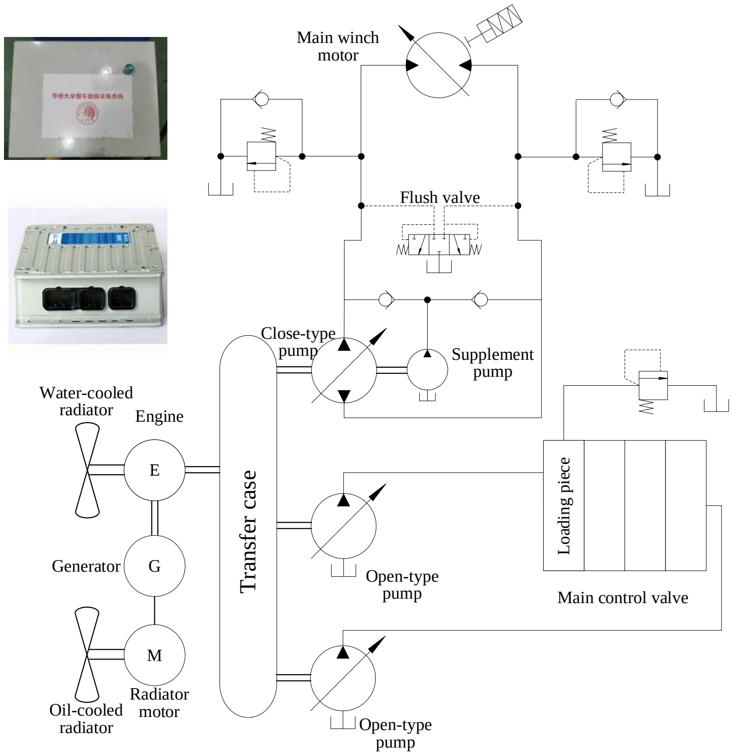


Figure 1. Hydraulic energy storage and driving schematic diagram of the winch lifting system.

3. System Characteristic Analysis

3.1. Working Condition Analyses

The common closed hydraulic system of winch lifting is composed of a "motor-pump-engine" system which has torque characteristics. When the winch is descending, the gravitational potential energy of descending weight is transferred to the engine through the winch, reducer, winch motor, four-quadrant pump, and transfer case. The load torque T_L generated by the gravitational potential energy drives the winch motor to rotate and output high-pressure oil, where the winch motor works in pump mode. The load torque T_L is the torque converted to the winch motor shaft, which is equivalent to the input torque T_m of the winch motor and can be expressed as

$$T_L = T_m \tag{4}$$

where, T_L is the load torque. T_m is the input torque of the winch motor.

The high-pressure oil output from the winch motor drives the four-quadrant pump/motor to rotate and works in the motor mode. Due to the fact that the engine is directly connected to the four-quadrant pump through the transfer case, it becomes the load of the four-quadrant pump. While the engine has a rotational acceleration trend when the engine is dragged.

When the engine itself absorbs negative power capacity and can balance the load, the torque on the output shaft which is the engine connected to the four-quadrant pump/motor is equivalent to the output torque T_p of the four-quadrant pump.

According to the torque formula $T = \frac{\Delta p D}{2\pi}$, the engine drag torque is related to the system pressure difference and pump displacement. To reduce engine drag torque in the traditional closed system, the control for increasing motor displacement or reducing pump displacement is often employed. Yet the traditional closed system would reduce the descending speed and affect the efficiency of the whole machine. To avoid this problem, an open-structure part which is connected to the close-structure part through the transfer case is proposed in Figure 1. The open-structure part can improve the descending speed, and high efficiency and energy saving can be achieved.

3.2. Four-Quadrant Pump/Motor Energy Consumption Analysis

Starting from its internal structure, the energy consumption of the four-quadrant pump/motor is analyzed. It is assumed that the four-quadrant hydraulic pump has the general axial piston pump volume loss and mechanical loss. In a real hydraulic system, volume loss is susceptible to compression, leakage, and compressibility of the fluid. While the viscosity, coulomb friction, and hydrodynamic friction lead to mechanical loss.

The mechanical loss can be described as,

$$T_{\text{loss}}(\alpha, \omega_{\text{p}}, \Delta p) = \Delta T_1 + \Delta T_2 + \Delta T_3 \tag{5}$$

where T_{loss} is the mechanical loss. α is the pump tilt angle. ω_{p} is the pump angular velocity. Δp is the pressure difference between the two ports of the pump. ΔT_1, ΔT_2 and ΔT_3 are the torque loss due to viscosity, leakage, and fluid compression in the four-quadrant pump, respectively.

The effective flow rate q_{Vp} of the four-quadrant pump can be expressed as,

$$q_{\text{Vp}} = D_{\text{p}}\omega_{\text{p}} - q_{\text{loss}}(\Delta p, \omega_{\text{p}}) \tag{6}$$

where q_{loss} is the sum of the system leaks. D_{p} is the pump displacement.

3.3. System Energy Consumption Analysis

Through the working condition analysis, the energy transferred to the four-quadrant pump/motor is along the following path shown in Figure 2. As can be seen, the energy loss of the gravitational potential energy transferred back to the engine goes through several energy loss links. As a result, the actual recovery rate of the gravitational potential energy can be expressed as

$$\eta_{\text{g}} = \eta_{\text{m}}\eta_{\text{v}}\eta_{\text{p}} \tag{7}$$

where, η_{g} and η_{p} are the gravity potential energy recovery rate and the four-quadrant pump/motor energy recovery effective utilization rate, respectively.

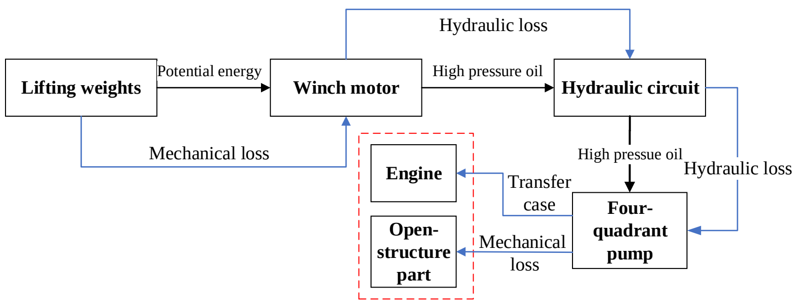


Figure 2. Energy transferred path.

4. Simulation Analysis

According to the working principle shown in Figure 1, the AMESim models are built to verify the feasibility of the proposed energy recovery system. In order to further analyze the controllability and energy-saving of the proposed system, the original open system model is also established. The models are given in Figure 3. As can be seen, compared to the original open system, the proposed system has the hydraulic energy recovery system.

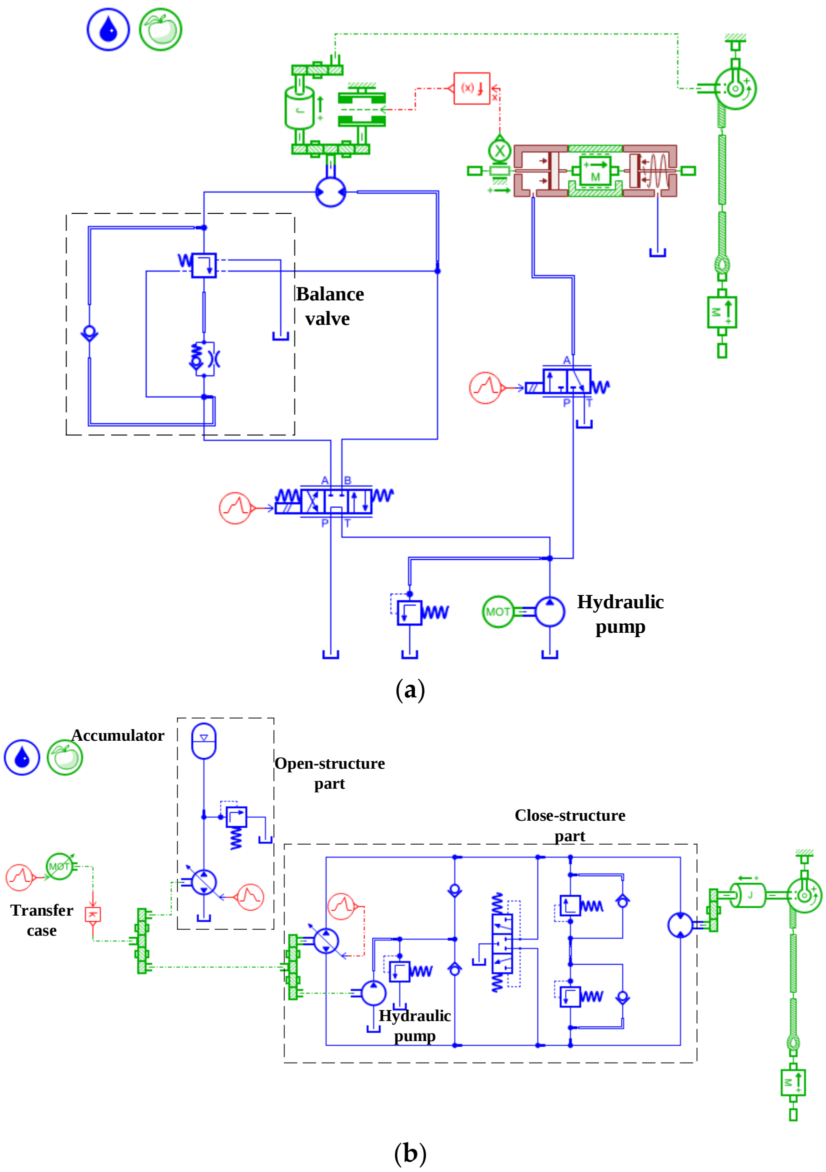


Figure 3. AMESim models of the original open system and proposed system for winch. (**a**) Original open system; (**b**) Proposed system with energy-saving.

To simplify the simulation model, the energy is recovered and released by the accumulator in the open-structure part to realize the flow regeneration in the process of winch lifting and descending.

Compared to the original open system, which needs a balance valve to stabilize the lower working condition, the proposed system with energy-saving adopts the volume speed regulation principle and can avoid the energy loss on the balance valve. Due to the fact that the two systems work in different principles, to ensure the same control requirement, the parameters need to be re-matched. The re-matched parameters of the two systems are given in Table 1.

Table 1. Parameters match of the two systems.

Parameter	Original Open System	Proposed System with Energy Saving
Engine speed/(rpm)	2050	1900
Specific fuel consumption/(g/kWh)	239	208
Transfer case speed ratio	/	1/0.76 = 1.31
Pump speed/(rpm)	2050	2500
System flow rate/(L/min)	430	$2 \times 235 + 450$
System pressure/(bar)	330	350
Lifting speed/(m/min)	45	53

The volume variation and the pressure variation of the accumulator in the proposed system are given in Figure 4, respectively. The displacement, the output flow of the winch motor, and the output power of the hydraulic pump in the process of winch lifting and descending of the two systems are given in Figure 5.

As can be seen in Figure 4, during the winch descending process, the accumulator is charged and its volume is reduced from 100 L to 39 L, and its pressure increases. When the winch stops, the accumulator pressure keeps constant. While during the winch lifting process, the accumulator volume increases to 100 L, and its pressure decreases. This indicates that the recovered energy by the accumulator is reused to lift the winch load.

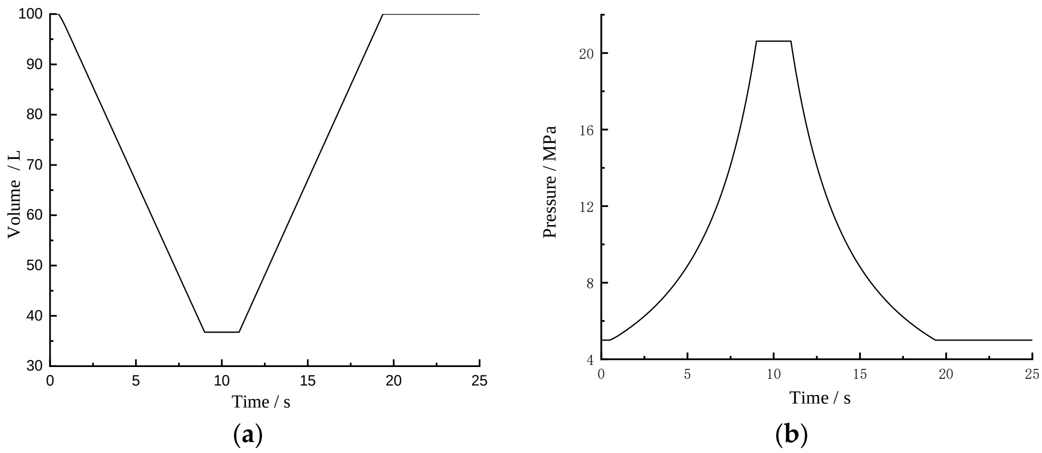


Figure 4. Volume and pressure change of the proposed system when winch lifting and descending. (**a**) Accumulator volume change; (**b**) Accumulator pressure change.

During the winch descending process in Figure 5a,b, the model is under the same ideal conditions. The parameters used in the two systems are obtained from the test prototypes of the two systems. To compare the characteristics, the models were carried out under the same lowering displacement. Compared to the original open system, the response of the proposed system with energy-saving is slower in the initial stage of descending. The main reason is that the speed regulation principle of the two systems is different, but the proposed system can still meet the operating speed requirements of the winch. At the same time, the proposed system with energy-saving has the flow regeneration function, which can reduce the engine output power by the gravity potential energy through the winch reverse torque. According to the working conditions analysis, the influence of reverse torque on system stability cannot be considered in the descending process, so the displacement of the four-quadrant pump/motor can be adjusted to the maximum value in the descending process. Compared to the simulation results in Figure 5, the winch descends faster in the actual system and can still reach the specified height at the end of operation compared with the open system. As seen from Figure 5c, in the winch lifting process, the pump output power of the proposed system is reduced from 150 kW to 40 kW, which is reduced by 73.3%. The proposed system with energy-saving has a remarkable energy recovery effect.

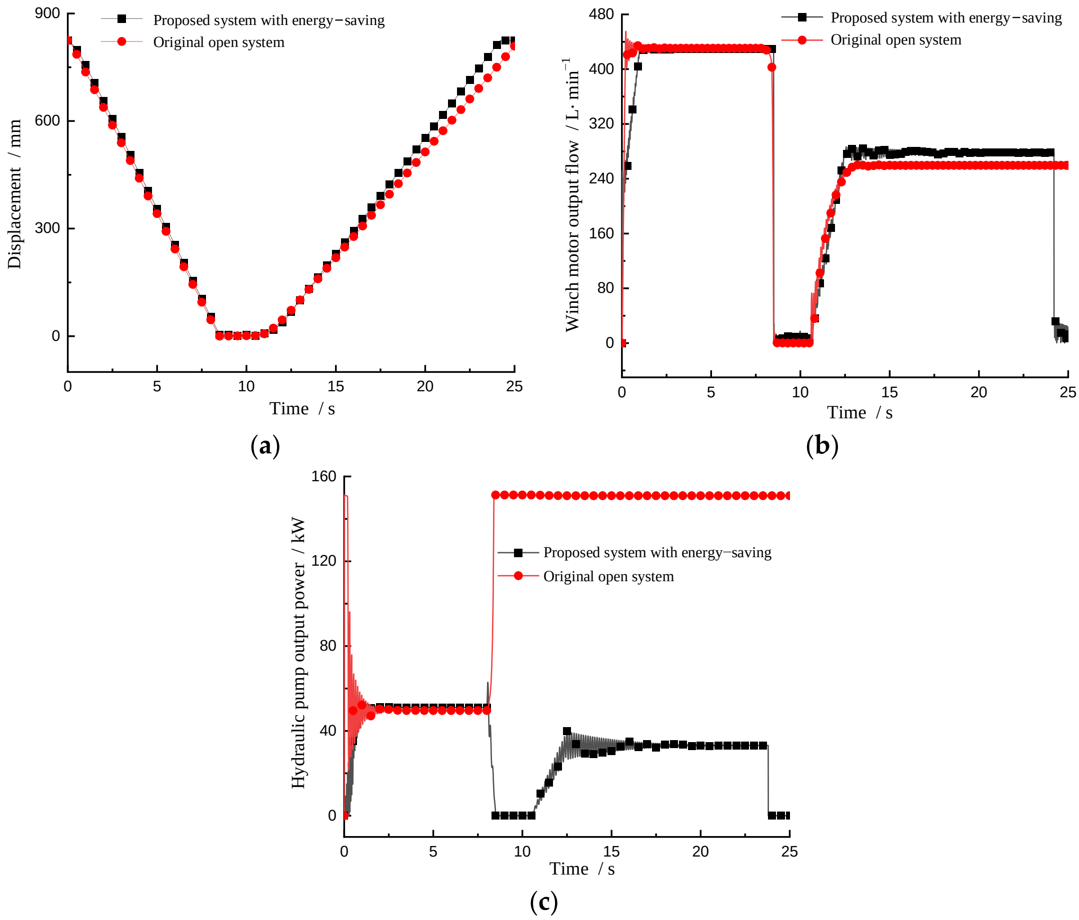


Figure 5. Characteristic comparison of the two systems through simulation. (**a**) Comparison of the winch displacement; (**b**) Comparison of the output flow of the winch motor; (**c**) Comparison of the output power of the hydraulic pump.

Although there is some flow fluctuation in the proposed system with energy-saving during the lifting process, it basically does not affect the actual working condition and safety of the whole machine. The faster lifting speed and the remarkable energy recovery effect can be obtained.

5. Test Analysis

5.1. Test System

The test prototype adopts two four-quadrant variable pump/motors, both of which are 90 mL/r, and the engine-rated speed is 1900 rpm. During the test, the Asmik MIK-P300 pressure sensor is used to test the pressure of the hydraulic pump and each actuator. The Parker SCFT-600-32-07 turbine flowmeter is used to test the output flow of the original open system and the proposed system with energy-saving. Meanwhile, the load rate, the speed, and the instantaneous fuel consumption of the engine are collected through wireless data acquisition. The sensors' data are collected by the slave computer and transferred to Ethernet devices through CAN bus, and then transmitted to the host computer through the wireless bridge. The host computer receives and processes the data using LABVIEW software (version: 2018. National Instruments, Austin, TX, USA). The test prototype and photos of each part are given in Figure 6.

Figure 6. Test prototype and the photos of each part.

5.2. Winch Operation Characteristics

The winch system with hydraulic energy storage system is adopted. The winch completes the lifting and descending working cycle under a constant speed of 1800 rpm, and the curves of the winch displacement, the pressure of the four-quadrant variable pump/motor, the open pump, and the winch motor are shown in Figure 7.

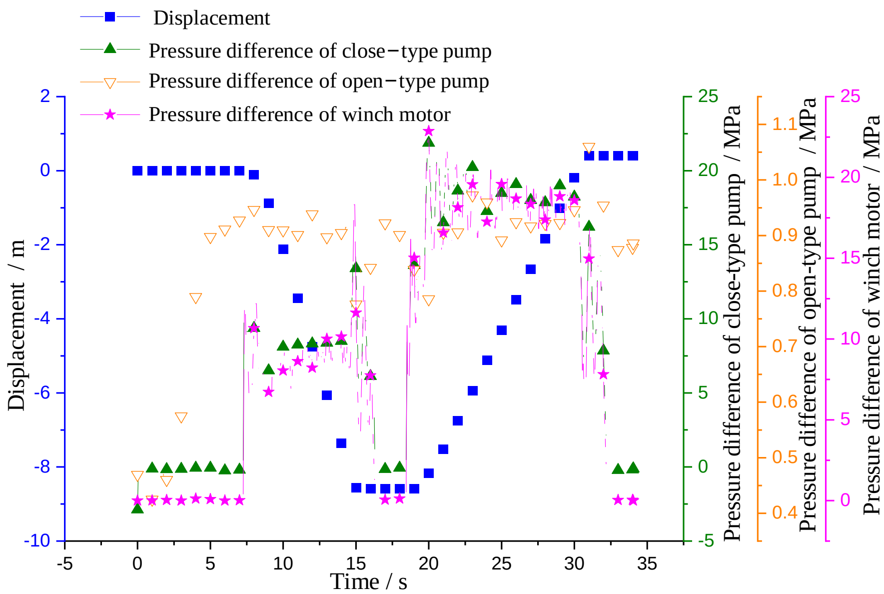


Figure 7. Winch operation characteristics under a working cycle.

In the working cycle, the winch falls during 7.5~15.2 s, and the winch lifts during 18.8~30.8 s. In the close-structure part, the pressure differences of the four-quadrant hydraulic pump and the winch motor are almost the same. The pressure is larger during the winch lifting process than that during the descending process. During the lifting process, it needs to overcome the load mass and the wind resistance which leads to a higher pressure and a larger fluctuation, while during the descending process the motor is directly connected to the pump in the close-structure part, which can reduce the energy loss on the balance valve. The open-structure part pressure can be obtained by the pressure differences of the open pump. According to Figure 7, the open-structure part pressure is basically maintained at a low value, which indicates that there is not too much drag torque of the winch motor to be balanced by the open-structure part.

5.3. Winch Energy Consumption Characteristics

To study the different working-condition influences on energy consumption with hydraulic energy saving, the tests under different load masses and different engine speeds are carried out. Seven different working conditions of the winch are shown in Table 2 and the characteristic curves are shown in Figures 8 and 9. The first three conditions are under different engine speeds with the same load mass and the last four conditions are under different load masses with the same engine speed. The load mass of the winch is very large which excesses of 5.5 tons.

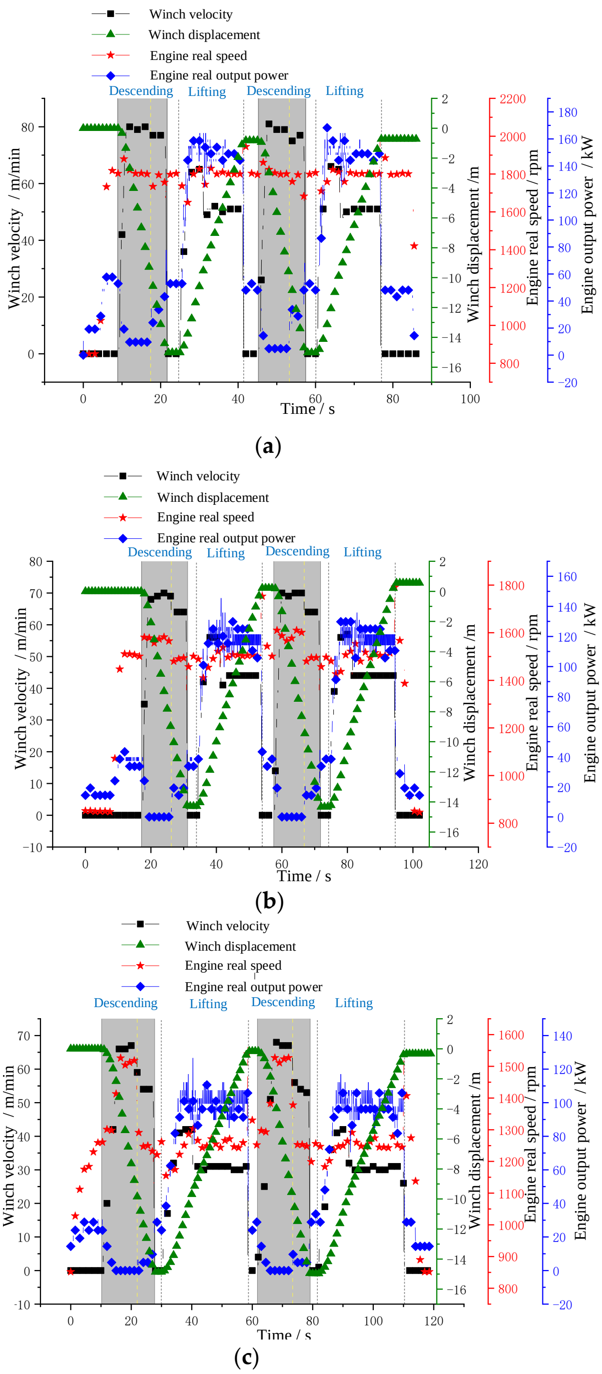


Figure 8. Characteristic curves under different engine speeds. (**a**) Engine speed and power, winch displacement and velocity under Condition 1; (**b**) Engine speed and power, winch displacement and velocity under Condition 2; (**c**) Engine speed and power, winch displacement and velocity under Condition 3.

Table 2. Different working conditions of the winch.

Item	Condition	Engine Speed/rpm	Load Mass/ton
Engine speed	Condition 1	1800	7.5
	Condition 2	1500	7.5
	Condition 3	1200	7.5
Load mass	Condition 4	1800	8.5
	Condition 5	1800	7.5
	Condition 6	1800	6.5
	Condition 7	1800	5.5

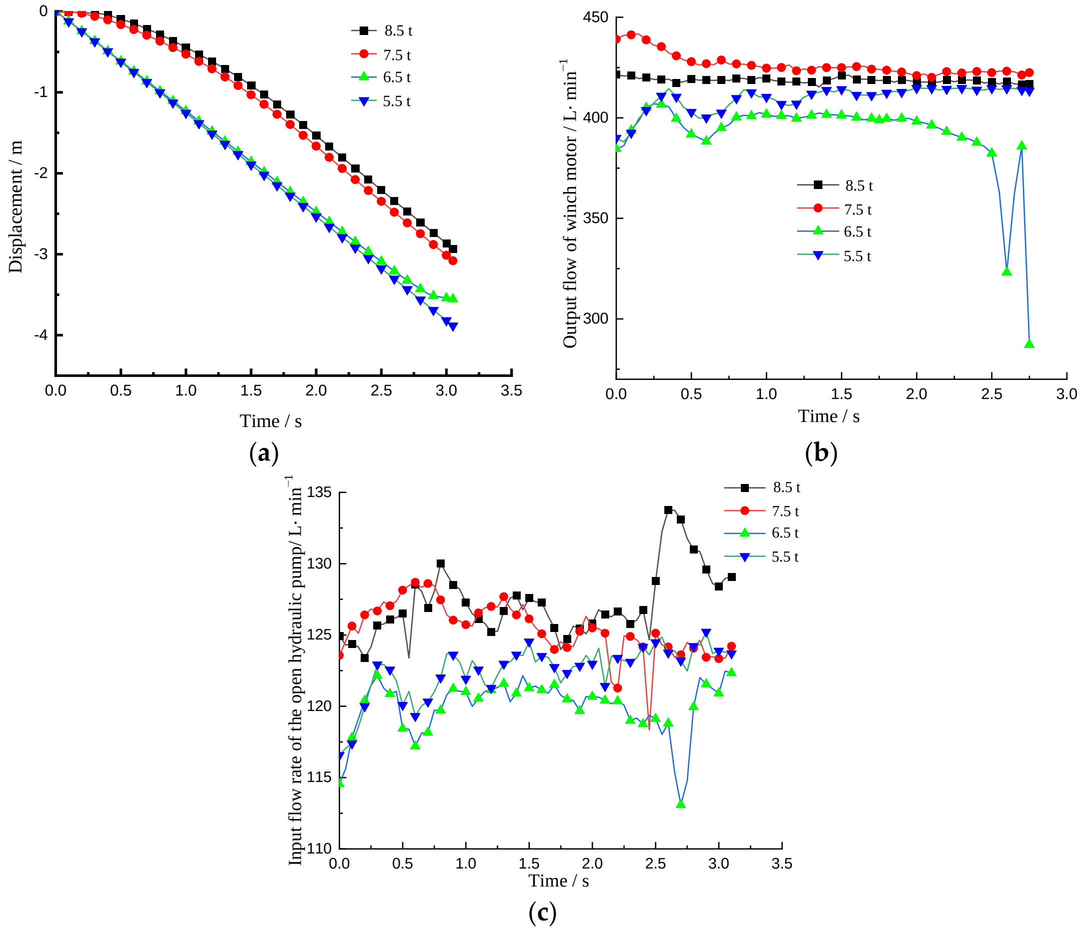


Figure 9. Characteristic curves under different load masses. (**a**) Displacement curves when winch descending; (**b**) Flow rate curves of winch motor; (**c**) Input flow rate of the open hydraulic pump.

The four-quadrant pump/motor power, the winch motor output power, and the open hydraulic pump input power can be deduced as

$$P_{\mathrm{p}} = \frac{D_{\mathrm{p}} n_{\mathrm{p}} \Delta p_{\mathrm{p}}}{0.76} \tag{8}$$

$$P_{\mathrm{m}} = Q_{\mathrm{m}} \Delta p_{\mathrm{m}} \tag{9}$$

$$P_{\mathrm{o}} = Q_{\mathrm{o}} \Delta p_{\mathrm{o}} \tag{10}$$

where, P_{p}, P_{m}, and P_{o} are the four-quadrant pump input power, the winch motor output power, and the open hydraulic pump input power, respectively. Q_{m} and Q_{o} are the flow rate of the winch motor and the open hydraulic pump, respectively. n_{p} is the actual speed of the four-quadrant pump. Δp_{p}, Δp_{m}, and Δp_{o} are the pressure differences at both ends of the four-quadrant pump, the winch motor, and the open hydraulic pump, respectively. The coefficient 0.76 refers to the transfer coefficient of the transfer case when the energy is transferred from the engine to the hydraulic part of the winch system.

According to Equations (8)–(10), the hydraulic pump output power and the winch motor power can be obtained.

5.3.1. Comparison under Different Engine Speed

When the engine speed is set at 1200 rpm, 1500 rpm, and 1800 rpm, respectively, the speed and the power of the engine, and the winch displacement are shown in Figure 8, respectively. Engine power increases with the increase of the engine speed. In addition, the proposed winch lifting system shown in Figure 1 can make full use of the four-quadrant pump/motor to realize the flow regeneration function. Its most significant feature is to reduce the engine output power during the process of lower winding. The energy recovered by the four-quadrant pump/motor is supplied to the engine to reduce its output power, which can reduce the energy consumption caused by the potential energy storage and reutilization during the winch up and down. Therefore, the energy-saving performance of the system is improved. When the engine speed is low, the engine can achieve zero output power and zero fuel consumption after stable descending. While, when the engine speed increases, the engine cannot achieve zero output power and zero fuel consumption after stable descending. This is because with the increase of the engine speed, the system pressure increases, and the energy consumption increases accordingly. The recovered energy by the four-quadrant pump/motor is not enough to completely compensate for the engine output power, and the open-structure part basically does not need to realize the balancing torque function.

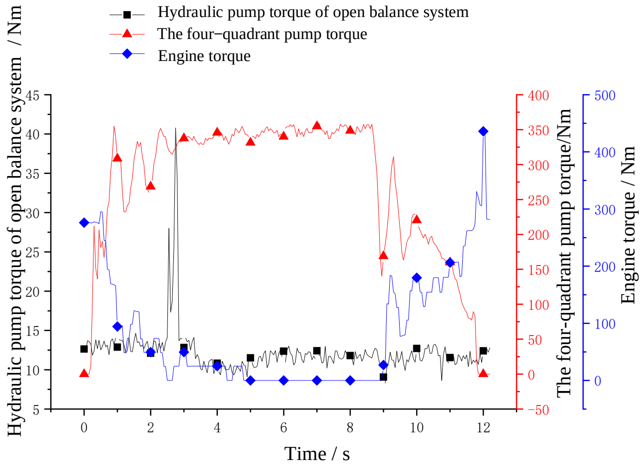
5.3.2. Comparison under Different Load Mass

As seen in Figure 9a, during the descending process, the change in load mass will affect the velocity change at the initial descending process. This means that when the load mass is larger, it takes the system a long time to reach stability. However, the change time is short, and the overall velocity change tends to be consistent after stability, so there is basically no influence on the actual control process. According to Figure 9b, the winch motor output flow is larger when the load mass is larger. As seen in Figure 9c, the flow rate of the open-structure part is less affected by load mass. Considering the above comparison of different engine speeds shown in Figure 8, the flow rate of the open-structure part is more affected by the engine speed, not the load mass.

From the above analysis of the seven working conditions, it is found that reducing the engine speed has a significant effect on energy consumption and the system is stable.

5.3.3. Comparison under Different Torque

In this study, the open system is used to achieve a stable and rapid system for winch lower process, namely a balance between energy saving and controllability. Therefore, considering the practical application, high speed and high load may produce “flying speed” phenomenon or speed overshoot phenomenon under the low speed condition. The hydraulic pump torque of the open system, the four-quadrant pump torque and the engine torque are compared under condition 3 and condition 4 listed in Table 2. Seen in Figure 10 that the system has an acceleration stage, a uniform speed stage and a deceleration stage during the process of the winch lowering. There is a slight hysteresis of motor torque compared to the four-quadrant pump/motor when entering the uniform speed stage. This indicates that the four-quadrant pump/motor works in hydraulic motor mode and the engine connected to the pump directly through transfer case. Therefore, the engine becomes the load of the four-quadrant pump/motor and the torque of them are inversely proportional. At the same time, when the negative power absorption capacity of the engine itself cannot balance the load, the open pump circuit will absorb the excess negative power.



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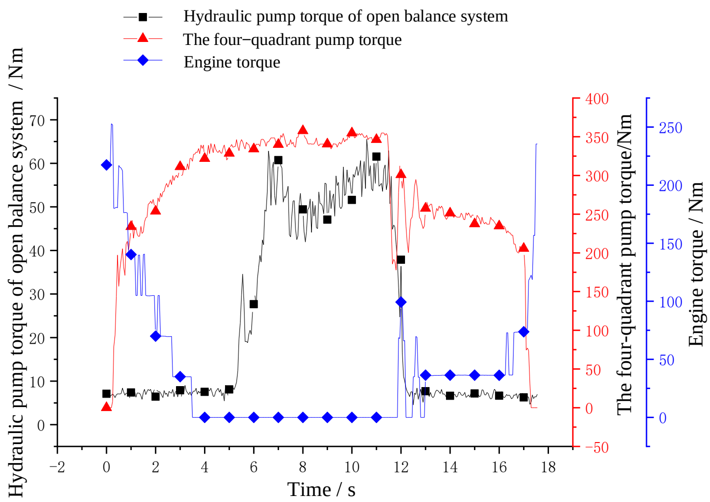


(**b**)

Figure 10. Characteristic curves under different torque. (**a**)Torque comparison diagram under condition 3; (**b**) Torque comparison diagram under condition four.

5.4. Utilization Efficiency of Recovered Energy with Four-Quadrant Hydraulic Pump

The utilization efficiency of the recovered energy is always a significant index to evaluate the energy-saving effect. The recovered energy during the descending process is defined as

$$E = \int_{t_0}^{t_1} P dt \tag{11}$$

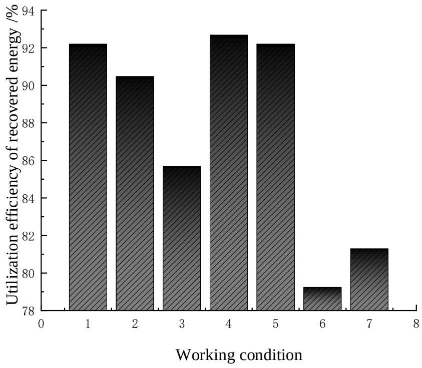
where, P denotes the power. t_0 and t_1 indicates the start time and the end time of the descending period.

The utilization efficiency of recovered energy with the four-quadrant hydraulic pump is defined as

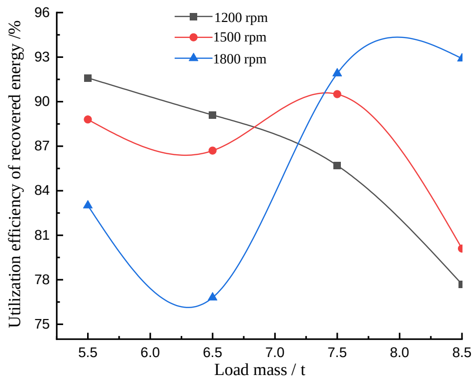
$$\eta_{\mathrm{p}} = \frac{E_{\mathrm{P}} - E_{\mathrm{o}}}{E_{\mathrm{P}}} \tag{12}$$

where, E_{p} and E_{o} are the input energy with the four-quadrant pump/motor and the energy consumed by the open-structure part.

In the actual test, the efficiency is tested through seven work conditions, as shown in Figure 11.



(**a**)



(**b**)

Figure 11. Utilization efficiency of recovered energy with four-quadrant hydraulic pump. (**a**) Comparative test of 7 working conditions shown in Table 2; (**b**) Utilization efficiency of recovered energy under different load mass.

The comparison of the effective utilization rate of energy recovery under the comparison of seven typical working conditions listed in Table 2 are given in Figure 7. As seen in Figure 11a, the utilization efficiency of recovered energy with the four-quadrant pump/motor is higher than 78% under the seven typical working conditions. Figure 11b indicates that there is a turning point in the efficiency curve of recovered energy with four-quadrant hydraulic pump/motor, which is the economic zone of the recovery efficiency of the proposed system in theory. Considering the three curves under different engine speeds, when the engine speed is set at 1200 rpm, the utilization efficiency of recovered energy continues to decrease, and it is speculated that the theoretical maximum recovery efficiency at 1200 rpm is in the region with less load mass. While the engine speed is 1500 rpm, the maximum utilization efficiency is achieved at 7.5 t. When the engine speed is 1800 rpm, with the increase of the load mass, the utilization efficiency of recovered energy is still in the high efficiency range and does not decline. This indicates that the maximum utilization efficiency is achieved after the load mass is larger than 8 t under 1800 rpm speed.

Combined with the simulation result in Section 4, to simulate the flow regeneration, an accumulator is used to simulate the open structure unit in the simulation model. Therefore, there is a process of energy conversion. The energy saving is 73.3%. While during the actual test, there is less energy conversion process and a higher energy saving can be achieved, which is larger than 78%. This verifies the accuracy of the simulation model and the reference of the simulation results. Meanwhile, in the actual test, to make the utilization efficiency of the recovered energy with a four-quadrant hydraulic pump/motor in the economic area, different load mass is chosen under different engine speeds to achieve the highest efficiency.

6. Conclusions

Based on the four-quadrant hydraulic pump/motor, the energy savings of the winch lifting system is studied and some useful conclusions are obtained.

(1) A hydraulic energy storage driving principle is used to recover the gravitational potential energy in the winch system, which can significantly reduce the energy consumption of the winch-driving system. The simulation results show that energy consumption can be reduced by up to 73.3%.

(2) Proposed hydraulic energy storage driving for the winch system can reduce the engine output power during winch descending. Additionally, the utilization efficiency of the recovered energy with four-quadrant hydraulic pump/motor is considerable, which can meet the needs of actual construction machinery.

(3) Compared with the original open-type no-energy saving system, the experimental prototype using a hydraulic energy storage driving system has realized the improvement

of utilization efficiency under different engine speeds and different load masses. Especially in the descending process, the energy consumption has been reduced by 87%. It has the remarkable effect of energy saving and emission reduction.

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