IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 5, 2019, accepted August 27, 2019, date of publication September 2, 2019, date of current version September 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2938824

Research on Response Characteristics and Energy Efficiency of Power Unit Used for Electric Driving Mobile Machine

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This work was supported by the National Natural Science Foundation of China under Grant No. U1510206 and Grant No. 51775364.

ABSTRACT Nowadays, the hydraulic pump driven by the diesel engine is widely used as the power unit for mobile machines, which consumes a large amount of fuel and cause high emissions. One solution is to use the electric driving mode. In this paper, the energy consumption characteristics of 4 electro-hydraulic power units, which are a fixed speed motor or a variable speed motor to drive a fixed displacement hydraulic pump or a variable displacement hydraulic pump, are compared and analyzed respectively. The results show that the power unit which a variable displacement hydraulic pump is driven by a variable speed asynchronous motor has the highest cost-performance ratio. However, due to the limitation of the battery peak current, the dynamic response of the power unit is slow. To solve this problem, a new power unit is proposed which add an accumulator to the hydraulic pump outlet to recover the power unit braking kinetic energy. The high-pressure oil stored in the accumulator can be absorbed into the hydraulic pump inlet to improve the power unit starting and braking performance and energy efficiency. The starting and braking characteristics of the power unit with and without the accumulator are compared experimentally. The results show that, if the power unit is driven by the motor alone, the power unit response is slow, and the load pressure has a significant influence on the response time. After adding the accumulator to the hydraulic pump, the power unit starting and braking time could be shortened significantly, and the starting power demand is also reduced. The proposed power unit is further used to drive a hydraulic excavator. Under the same working conditions and operating characteristics, energy consumption can be reduced by 28.5% compared with using the variable displacement hydraulic pump alone.

INDEX TERMS Mechanical engineering, electro-hydraulic power unit, experiment research, hydraulic excavator, starting and braking performances.

I. INTRODUCTION

The variable displacement pump driven by the diesel engine is widely used as the power unit in mobile machines. The engine power is configured based on the maximum working load. In the actual operation, the hydraulic excavator works largely in the partial load condition. Therefore, the system output power is not matched with the load, and the engine works in the low-efficiency zone for a long time, resulting in low energy efficiency and severe emission.

Some researchers are using hybrid power technology to solve these problems. In order to make the engine better match the load, more than one kinds of power units are used to drive the hydraulic pump, which is called hybrid technology. By combining different power units and making full use of the advantages of each power unit, the overall efficiency of the power system can be improved, and the installed power can be reduced [1], [2]. In the existing hydraulic excavators which adopting hybrid power technology, the engine was still used as the main power unit. OCHIAI *et al.* compared the fuel efficiency of hybrid excavators in the series type and parallel type by simulation [3], [4]. The results showed that around 24% of energy consumption could be reduced by using the hybrid power unit. Jaewoong Choi *et al.* proposed an optimization method for the power system based on dynamic programming. The control algorithm was verified by simulation

The associate editor coordinating the review of this article and approving it for publication was Jianyong Yao.

and field test, and the results showed that fuel consumption can be reduced by 26% [5], [6]. Wang *et al*. studied the parallel type hybrid system with the capacitive energy storage, and proposed the self-judging multi-point switching control strategy and the dynamic control strategy [7], [8]. He *et al*. proposed an operating point control strategy for the parallel type hybrid system based on the working condition prediction. The simulation results showed that the fluctuation of the supercapacitor charging state could be reduced effectively, the engine could work in the high-efficiency zone stably, and the fuel economy could be improved significantly [9].

In summary, the hybrid power technology could improve the engine energy efficiency to some extent. But the cost will be increased and the engine is still used as the power unit, whose fuel conversion efficiency is only around 40%. As a result, energy efficiency improvement is very limited. At the same time, the emission problems are still there. For this reason, the purely electric driving mobile machine with the electro-hydraulic power unit has become the new development trend gradually [10].

The traditional electro-hydraulic power unit is a hydraulic pump driven by a fixed rotational speed motor [10]. Hydraulic pumps can be divided into fixed displacement hydraulic pumps and variable displacement hydraulic pumps. The power unit which a fixed displacement hydraulic pump is driven by a fixed rotational speed motor has significant throttling loss and overflow loss [11]. In order to reduce the energy consumption of the hydraulic power unit, the ideal way is to use the variable displacement hydraulic pump as the power unit with pressure, flow and power combined control, so that the output pressure and flow of the hydraulic pump could match the load [12], [13]. However, if the system is in the partial load condition or the non-working period, the energy loss is sitll significant [14], [15] when the pump output flow and pressure are controlled by adjusting the hydraulic pump displacement with a fixed rotational speed. For this reason, some researchers proposed a power unit which the variable speed motor drives the fixed displacement hydraulic pump or the variable displacement hydraulic pump.

Mitsubishi Corporation of Japan proposed the variable frequency volume speed control method first and applied it to hydraulic elevators. By adjusting the motor speed, the flow rate of the fixed displacement pump, as well as the speed of the elevator, could be controlled, and the noise and energy consumption can be reduced [16]. TANAKA *et al*. used the electro-hydraulic power unit which a fixed displacement hydraulic pump is driven by a variable speed asynchronous motor to drive the double-rod hydraulic cylinder system. The energy consumption characteristics of four hydraulic power units, which are a fixed speed asynchronous motor or a variable speed asynchronous motor to drive a fixed displacement hydraulic pump or a variable displacement hydraulic pump, were studied respectively [17]–[19]. The results showed that a variable speed motor to drive a variable displacement hydraulic pump has the highest energy efficiency. Then, the electro-hydraulic power unit, which a servo motor is used to drive the hydraulic pump, is applied to the hydraulic system of the injection molding machine, and the system dynamic response has improved [20]. LOVEREC *et al*. applied the electro-hydraulic power unit to the hydraulic brake system of the forming machine, the energy consumption has been reduced and the safety has been improved [21]. Quan *et al*. applied the electro-hydraulic power unit to the hydraulic system of the injection molding machine and the hydraulic excavator, and the energy consumption was reduced significantly [22], [23].

Through the analysis and comparisons above, instead of using the diesel engine, in this paper, the variable displacement hydraulic pump driven by the variable speed asynchronous motor is used as the power unit to improve the energy efficiency, reduce the installed power, and solve the emission problems thoroughly. However, the dynamic response of the power unit is slow which has already affected the manipulation of the machine. To solve this problem, a new technical scheme is developed in which a hydraulic accumulator is added to the hydraulic pump outlet, and the high-pressure oil stored in the accumulator can be absorbed into the hydraulic pump inlet to improve the starting and braking performance of the power unit, as well as the energy efficiency. The key parameters of the components are determined through the analysis of the power unit running performance. The power unit prototype is established to verify the effectiveness of the proposed method. Further, the purely electric driving hydraulic excavator prototype is established to verify the feasibility of applying the power unit on the actual machine.

II. COMBINATION MODES OF THE POWER UNIT

Existing mobile machines always use the diesel engine as the power unit, and hydraulic pumps are mainly variable displacement pumps. If the electric motor is used as the power unit, the hydraulic pump can be either a fixed displacement pump or a variable displacement pump.

There are three control modes according to the different combinations: the variable displacement hydraulic pump driven by the constant speed asynchronous electric motor (VDCM), the variable displacement hydraulic pump driven by the variable speed electric motor (VDVM), and the fixed displacement hydraulic pump driven by the variable speed electric motor (FDVM). Variable speed electric motors include variable frequency asynchronous electric motor and servo electric motor [10]. Fig. 1 shows the combination modes and control principles of three electric driving power units mentioned above. In Fig. 1, n is the given signal of the motor rotational speed, and α is the given signal of the hydraulic pump displacement.

Similar to the power unit driven by the diesel engine, the variable displacement hydraulic pump driven by the constant speed asynchronous motor could control the hydraulic pump output flow and pressure by changing the displacement of the hydraulic pump. When the load is light or the system

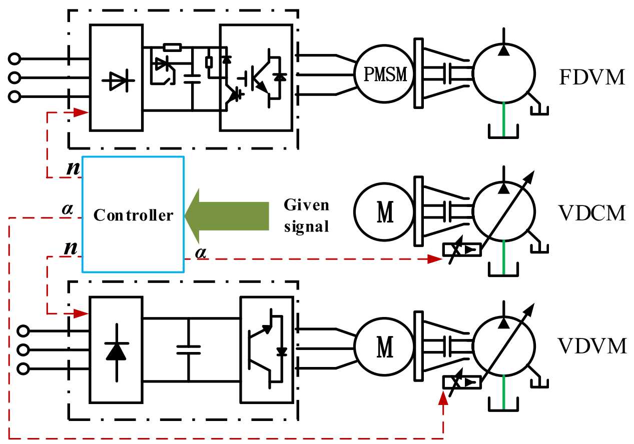


FIGURE 1. Different combination modes of power unit.

runs in idle working condition, the motor still works at rated speed, which results in severe energy loss [14].

In order to improve the energy efficiency of the variable displacement pump driven by the asynchronous motor, the speed of the motor can be adjusted. The power unit energy efficiency will be improved by optimizing the combination of the motor speed and the hydraulic pump displacement.

In the combination of the fixed displacement pump and the electric motor, there are two choices for the motor: the asynchronous motor or the servo motor.

When using the servo motor to drive the fixed displacement hydraulic pump, the closed-loop control of the pressure and flow can be achieved by adjusting the rotational speed of servo motor, the dynamic response is fast and the control precision is high. However, the cost of the servo motor is too high to adapt to the hush working environment. Once the speed and pressure sensors are malfunctioning, the machine has to stop.

When using the asynchronous motor to drive the fixed displacement pump, the output flow of the hydraulic pump could also be controlled by adjusting the motor speed, but the dynamic response is slow. Besides, it is difficult to achieve the closed-loop control for the pressure with this method.

Based on the previous analysis, the electronic proportional variable hydraulic pump with the variable speed asynchronous motor driving is proposed as the power unit. In addition, a hydraulic accumulator is added and the high-pressure oil stored in the accumulator is absorbed into the inlet of the hydraulic pump to assist the power unit in driving, and to improve the electric motor dynamic response, the braking performance, and energy efficiency of the power unit.

III. KEY PARAMETERS ANALYSIS OF THE ELECTRO-HYDRAULIC POWER UNIT

In order to get the basic parameters of the new electro-hydraulic power unit system, it is necessary to analyze the influence of the parameters of the variable frequency asynchronous motor on the starting and braking characteristics of the system, so as to provide a theoretical basis for establishing the relevant experiment scheme.

At present, there are four commonly used ways to adjust the motor speed by frequency conversion: constant voltage-frequency ratio control, slip frequency control, vector control and direct torque control. In this paper, the vector control method is used which is of high dynamic response and low cost. If the frequency is lower than 50 Hz, the motor is controlled by the constant torque, If the frequency is higher than 50 Hz, the motor is controlled by the constant power. With this control method, using a single hydraulic pump could realize the function of the double-pump which is a large flow rate with low pressure and, or a small flow rate with high pressure.

The torque balance equation of asynchronous motor is

$$\frac{3n_pL_m\lambda_r i_{qs}}{2L_r} = \frac{D_p(p_o - p_i)}{2\pi\,\eta_{pm}} + J\frac{d\omega}{dt} + D\omega \tag{1}$$

where $\frac{D_p(p_o-p_i)}{2\pi\eta_{pm}}$ is the resistance torque of hydraulic pump, $\frac{3n_pL_m\lambda_r i_{qs}}{2L_r}$ is the electromagnetic torque of motor, ω is the angular speed of the motor, J is the rotational inertia of the power unit, D is the damping coefficient, n_p is the the pole-pair number of the motor, L_m is the magnetic inductance, L_r is the self inductance of rotor winding, i_{qs} is the component of torque generated by stator current, λ_r is the rotor flux, p_o is the hydraulic pump output pressure, p_i is the hydraulic pump input pressure, D_p is the hydraulic pump displacement, η_{pm} is the mechanical efficiency of the hydraulic pump.

In the working process, in order to improve the stability of the motor operation, it is necessary to increase the installed power of the frequency converter and to increase the overload capacity, which will have a greater impact on the power supply. Eq. (1) shows that if the hydraulic pump resistance moment is changed into the driving torque without increasing the supply current, the acceleration of the motor starting and braking will be increased and the system dynamic response speed will be improved.

Therefore, an accumulator is added to the hydraulic pump outlet. When the motor is starting, the high-pressure oil stored in the accumulator is absorbed into the hydraulic pump inlet. At this time, the hydraulic pump is transformed into the hydraulic motor, so that the load torque becomes the driving torque to drive the hydraulic pump. When the motor is braking, the output of the hydraulic pump connects to the accumulator inlet, and the motor kinetic energy is recovered. Meanwhile, the braking speed is increased.

Eq. (1) shows that the resistance torque generated by the hydraulic pump is proportional to the pressure difference between the hydraulic pump inlet and outlet, and the hydraulic pump displacement. The hydraulic pump displacement can be obtained based on the system operating speed. According to the system inertia, as well as the motor rated torque and the required response time, we can calculate the appropriate working pressure and volume for the accumulator to meet the system dynamic requirements.

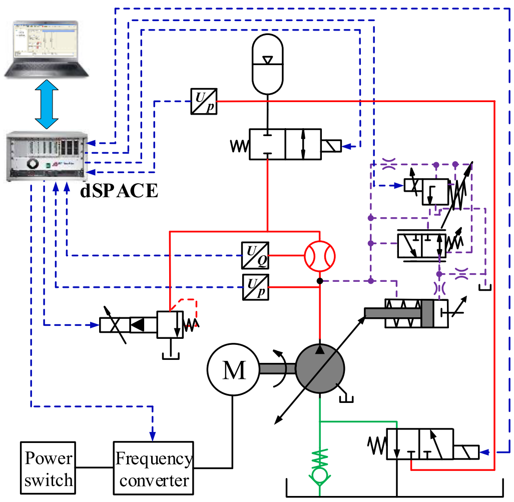


FIGURE 2. Experimental system of electrohydraulic power unit assisted by accumulator.

IV. DYNAMIC AND STATIC CHARACTERISTIC EXPERIMENT

According to the analysis of the key parameters for the electro-hydraulic power unit, the types of the variable frequency asynchronous motor, the hydraulic pump, and the accumulator can be determined. Then the experiment system is established, the dynamic and static characteristics of the electro-hydraulic power unit are studied, and whether the power unit could meet the requirement is verified.

A. EXPERIMENTAL SYSTEM PRINCIPLE

The experimental system for the electrohydraulic power unit assisted by the accumulator is shown in Figure 2. The power unit running performance is studied through experiments, which provide a basis for its application in mobile machines.

The rotational speed of the AC asynchronous motor is controlled by the frequency converter with the vector control in the experimental system. The electronic proportional hydraulic pump with the displacement of 71 ml/r is used, whose pressure and flow can be adjusted continuously. The hydraulic pump outlet is connected with an electric proportional relief valve which is taken as the loading valve. The hydraulic pump absorbs oil from the tank or accumulator. The volume for the hydraulic accumulator is 16 L. The outlets for the hydraulic pump and the accumulator are both equipped with pressure sensors, and the hydraulic pump outlet is equipped with a flow sensor. The variable-frequency motor input power is measured by an electric power meter. The sensors testing data are processed by the hardware in-the-loop test system of dSPACE.

B. STARTING AND BRAKING CHARACTERISTICS OF ACCUMULATOR AUXILIARY POWER UNIT

1) DRIVEN INDEPENDENTLY BY MOTOR

The variable frequency asynchronous motor starts and brakes frequently with variable rotation speed control. As a result, the starting and braking performance of variable frequency asynchronous motor with different loads are studied. In the experiment, the initial speed for the motor is set to 0, and the motor maximum starting current is constrained by the frequency converter to the rated current and 1.5 times of the rated current for comparison. The loading valves pressure control values are set to 0.5 MPa, 6 MPa, 12 MPa, and 18 MPa, respectively. In the experiment, the motor speed increases from 0 to 1500 r/min first, and then decreases from 1500 r/min to 0. During the whole process, the response speed of the hydraulic pump output flow is measured in real-time. Figure 3 shows the starting and braking performance of the electro-hydraulic power unit with two different currents.

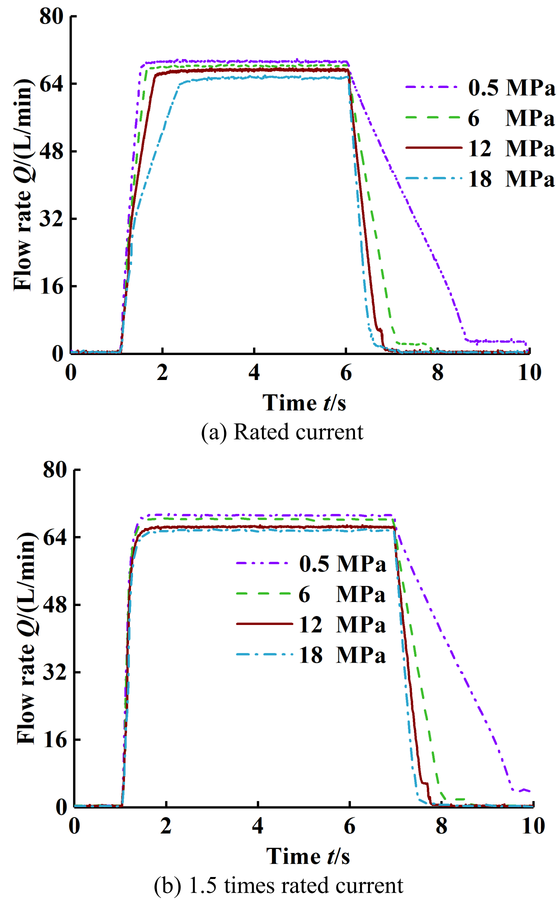


FIGURE 3. Starting and braking performance of the electrohydraulic power unit with different current.

It can be seen from Fig. 3(a) that the load pressure has a significant influence on the flow response performance of the electro-hydraulic power unit with the rated current. When the load pressures are 0.5 MPa and 18 MPa, the starting response times are 0.58 s and 1.43 s respectively, and the braking response times are 2.65 s and 0.88 s respectively. It can be concluded that, when the staring current is the rated current, the starting response time for the power unit increases with the increasing of the load pressure. In addition, as the motor has no braking resistance, the external load is needed for braking. The higher the load pressure is, the shorter the braking time will be.

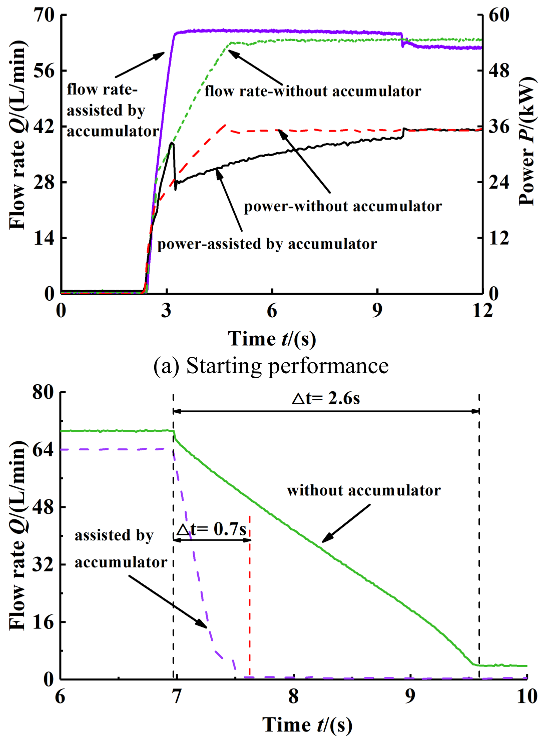


FIGURE 4. Starting and braking performance of the electrohydraulic power unit assisted by accumulator.

FIGURE 5. Experiment system of pure electric driving hydraulic excavator.

Fig. 3(b) shows the experiment results with 1.5 times of the rated current. When the load pressures are 0 MPa and 18 MPa, the starting response times are both 0.58 s, and the braking response time is identical to the rated current scenario. It can be seen that when the starting current is large enough, the motor has enough torque to overcome the load torque to accelerate the motor starting process, and the output flow response time is almost not affected by the load pressure. In addition, the starting current has no influence on the braking response.

It can be concluded from the above curves that, when the system runs in the steady state, the motor speed and the pump output flow will decrease with the increase of the load pressure, which needs to be compensated in the practical application.

In summary, when the starting current is large enough, the system starting response time could meet the demands, but the capacity of the supercapacitor or the battery need to be increased, which is costly.

2) ASSISTED BY ACCUMULATOR

Fig. 4 shows the motor starting and braking performance with or without the assistance of the hydraulic accumulator under the rated current.

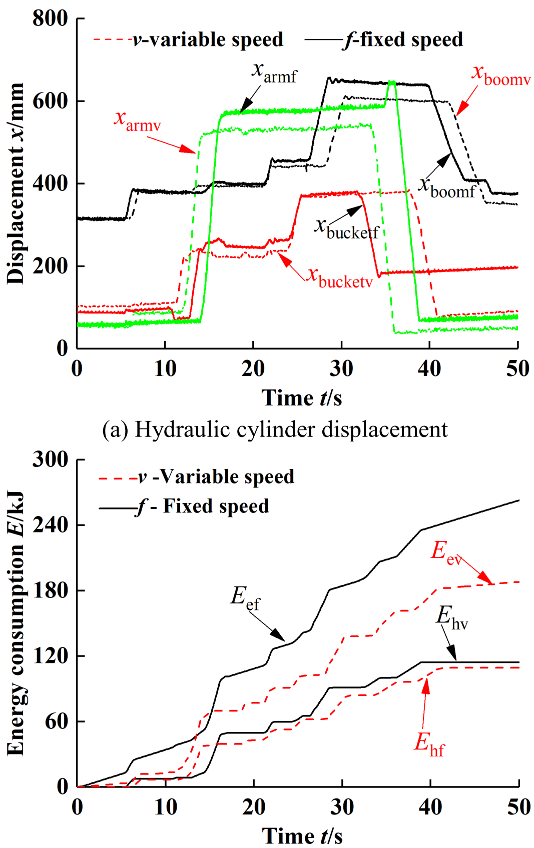
Fig. 4(a) compares the power unit starting performance with or without the assistance of the accumulator. When the load is 21 MPa, the power unit starting response time is 2.36 s without the assistance of the accumulator, while it is 0.66 s with the assistance of the accumulator, and the initial oil pressure of the accumulator is 18 MPa. The power unit starting power is lower with the assistance of the accumulator than that without the assistance of the accumulator. Fig. 4(b) shows the power unit braking performance. When the load is 0.5 MPa, the power unit braking time is 2.6 s without the assistance of the accumulator, while it is 0.7 s with the assistance of the accumulator, and the high-pressure oil from the hydraulic pump outlet is directly stored in the accumulator. The results show that adding the accumulator could shorten the power unit starting and braking time and reduce the starting power.

V. EXPERIMENT OF ELECTRIC DRIVING MOBILE MACHINE

Taking the hydraulic excavator as an example, the electronic proportional hydraulic pump driven by the variable frequency asynchronous motor is used to replace the diesel engine and the load sensing variable hydraulic pump. A pure electric driving hydraulic excavator experiment system is established as shown in Fig. 5. Due to the frequent action of the hydraulic excavator in the working process, the high response speed is required. The following section will compare and analyze the energy consumption characteristics of the excavator with two different driving modes, which are:

- Combined control of variable speed and variable displacement.
- Variable displacement control only.

Fig. 6(a) shows the hydraulic cylinder displacement curves for all actuators in a typical excavation cycle of a hydraulic excavator (the hydraulic cylinder displacement of the boom x_{boom}, the hydraulic cylinder displacement of the arm x_{arm}, and the hydraulic cylinder displacement of the bucket x_{bucket}). The whole excavation cycle includes compound excavation of the arm and bucket, lifting the boom, compound unloading of the arm and bucket, and lowering the boom to the initial position. In the working process, the accumulator is used to assist the power unit starting and braking processes. In the process of variable speed and



(a) Hydraulic cylinder displacement

(b) Energy consumption curve

FIGURE 6. **Energy consumption performance of the excavate cycle.**

variable displacement control, the reference motor speed is set. In the system stable operation process, the motor speed is maintained at the reference value. When the load varies significantly, the motor speed is adjusted to match the load.

Fig. 6(b) shows the energy consumption curve in an excavation cycle. When the combined variable speed and variable displacement control strategy is used, the electric energy consumption E_{ev} is 188.0 kJ, and the hydraulic pump output energy E_{hv} is 109.0 kJ. When the variable displacement control is used alone, the electric energy consumption E_{ef} and the hydraulic pump output energy E_{hf} are 262.9 kJ and 114.3 kJ, respectively. According to the above data, the energy efficiency of the electro-hydraulic power unit with the two control strategies are 58.0% and 43.5%, respectively. Compared with the variable displacement control, the combined variable speed and variable displacement control strategy could reduce the electric energy consumption by 28.5% in a complete excavation cycle.

VI. CONCLUSION

Using the variable displacement hydraulic pump driven by the variable speed asynchronous motor as the power unit, when the maximum starting current of the motor is the rated current, the starting response time for the electro-hydraulic power unit becomes longer when the load pressure is increasing; when the maximum starting current is 1.5 times of the rated current, the starting response time for the electro-hydraulic power unit is almost not affected by the load pressure.

The dynamic response speed of the electro-hydraulic power unit can be improved effectively after the hydraulic accumulator is used to assist the motor to start and brake. The method could also reduce the peak current and cost of the external power supply effectively.

Compared with variable displacement control, combining variable speed control and variable displacement control could reduce the electric energy consumption by 28.5% in a complete working cycle.

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