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An Electro Hydraulic Hybrid System to Downsize Motor Power of Electric Wheel Loader Working Function

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Abstract.
The electro-hydrostatic variable speed drive system (VSD) is one of the effective ways to improve energy efficiency of electric wheel loader working function. However, the VSD system still has the limitations including large installed motor power, low-efficiency operating points of the electric motor-pump, and high dynamic response requirement of components. Therefore, an electro-hydraulic hybrid variable speed drive system (EH-VSD) is proposed to reduce the installed power with maintaining the energy efficiency. Unlike VSD system that relies on motor speed control, the proposed solution incorporates a high-pressure hydraulic accumulator in parallel configuration. The electric motor-pump supplies the average power demand, while the accumulator responds to peak load requirements. An energy management strategy based on the dynamic programming is developed to manage the power distribution of two energy sources. Simulation results show that the installed motor power of EH-VSD system reduces by 54.5% compared to VSD system (from 110 kW to 50 kW). The EH-VSD system achieves a significant reduction in installed power while maintaining a high energy efficiency comparable to that of the VSD system, effectively avoiding substantial throttling losses.

Keywords. Electro-hydraulic hybrid system, variable speed drive, dynamic programming, installed power, electric wheel loader.

1. Introduction

With the growing global demand for energy conservation and emission reduction in construction machinery, traditional machines powered by internal combustion engines are increasingly unsuitable due to their high energy consumption, substantial carbon emissions, and severe environmental impact [1]. Electrification technology, which replaces conventional engines with electric motors powered by batteries or cables, enables zero emissions at the point of use and significantly improves system energy efficiency. Consequently, it has become a prominent research focus in the field of construction machinery [2].

To reduce energy consumption in the working system of electric wheel loader, an electro-hydrostatic variable speed drive (VSD) system has been proposed for application in wheel loaders [3], as illustrated in Fig. 1.1. This system controls the velocity of the hydraulic cylinder by adjusting the motor speed, thereby avoiding throttling regulation and improving overall energy efficiency [4]. Qu et al. applied an open-circuit VSD working system with an integrated motor-pump unit in a skid steer loader, achieving a steady-state energy efficiency of up to 59.9% [5]. Guo et al. proposed a VSD steering system for wheel loaders, which reduced energy consumption by 22.8% compared with conventional systems [6].

Although the VSD working system significantly improves energy efficiency, it still has certain inherent limitations due to its system configuration: 1) The high-magnitude and transient load demands characteristic of working hydraulic system requires substantial installed power when relying solely on motor-pump actuation. 2) The frequent load cycle variation compels the motor-pump unit to respond rapidly, often operating outside its optimal efficiency range. 3) The concurrent demands for high dynamic response, sustained energy efficiency, and high peak power result in increased system cost [7-10].

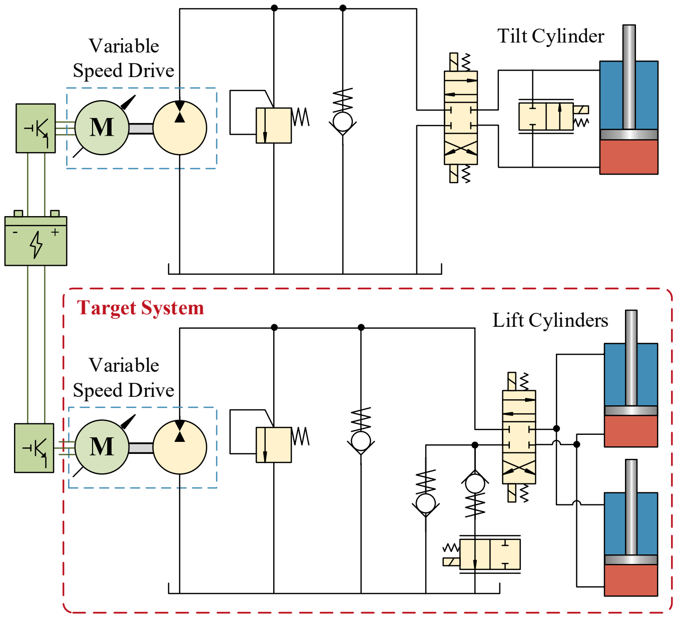


Fig. 1.1. The electro-hydrostatic variable speed drive (VSD) system (baseline system)

Compared with purely electric drive systems, electro-hydraulic hybrid drive systems integrate a secondary energy storage component, which expands the controllable dimensions and enables flexible energy distribution and conversion between different power sources, thereby facilitating improved overall performance [11-13]. Some recent studies have focused on electro-hydraulic hybrid control strategies for VSD working systems. Kang et al. proposed using an accumulator as a built-in regulator to enhance the dynamic performance of the VSD system, aiming to achieve faster response and broader frequency bandwidth [14]. Shang et al. introduced an energy recovery module into the variable-speed system, which disabled the generator mode of the motor under forward load conditions [15]. This configuration allowed the elimination of the system's power resistor and reduced electric motor heating temperature by 39%. Seo et al. employed a secondary control part in the VSD system, consisting of a high-pressure accumulator, a servo valve and mode-switching valves, to reconfigure the hydraulic circuit according to operational modes [16].

Therefore, an electro-hydraulic hybrid variable speed drive system (EH-VSD) is proposed for the working function of electric wheel loaders. Unlike VSD system that relies solely on motor speed regulation, the proposed solution incorporates a high-pressure accumulator in parallel configuration. The electro-hydraulic parallel design leverages the respective advantages of both components: the electric motor and pump unit (VSD unit) supplies the average power demand, while the accumulator responds to peak load requirements. This configuration effectively reduces the installed power, leading to a more compact and lightweight system, making it more suitable for powertrain layout design and contributing to lower electric drive costs. Meanwhile, the proposed system still utilizes the variable speed drive to maintain the throttle-free advantage.

The main contribution of this study is to propose an electro-hydraulic hybrid variable speed drive system (EH-VSD) to downsize the electric drive system. An energy management strategy based on the dynamic programming is developed to ensures the VSD unit operates within its high-efficiency region, which further improves the energy efficiency of the system. The comparison between proposed system and baseline system (VSD) is conducted in terms of system performance, installed power and energy efficiency. The rest of the paper is organized as follows: Section 2 presents system mathematical modelling and working modes, section 3 shows control strategy and optimization method, section 4 shows simulation study and comparison, and section 5 concludes the study.

2. SYSTEM CONFIGURATION

2.1. System overview

The schematic of the electro-hydraulic hybrid variable speed drive (EH-VSD) working system is illustrated in Fig. 2.1. In the working system of a wheel loader, the lift function accounts for over 80% of the total energy consumption and is characterized by high load power [17]. Therefore, this study focuses on the lift function as a representative case to investigate the performance of the proposed EH-VSD system.

The system's power sources consist of a VSD unit and a high-pressure hydraulic accumulator module. The VSD unit is composed of a lithium iron phosphate ($LiFePO_4$) battery pack, an inverter, a permanent magnet synchronous motor (PMSM), and a hydraulic pump. The PMSM is selected for its fast dynamic response, making it well-suited for variable-speed operation. A fixed-displacement, unidirectional hydraulic pump is employed in the system. The high-pressure accumulator module serves as a secondary power source, supplying additional energy to the system when required. The proportional valve 1 (PV1) is used to regulate the flow discharged from the accumulator and also allows the hydraulic pump to operate independently. Both the hydraulic pump and the accumulator adopted in the proposed system are commercially available hydraulic components.

The hydraulic system adopts an open-circuit configuration, in which the low-pressure pipeline and the pump inlet are directly connected to the hydraulic reservoir. The system switches between different operating modes using a directional valve (DV), with specific control strategies detailed in Section III. The proportional valve 2 (PV2) is employed to control the lowering speed of the hydraulic cylinder and remains fully open in the left position during other working modes. The check valve 1 (CV1) ensures unidirectional rotation of the hydraulic pump by preventing backflow from the accumulator, thereby avoiding interference with pump operation. The check valves 2 (CV2) and 3 (CV3) are used to control the flow direction between the hydraulic cylinder and hydraulic reservoir, enabling appropriate flow paths for different working modes. A relief valve (RV) is included as a protective component to prevent system pressure from exceeding the designated working pressure.

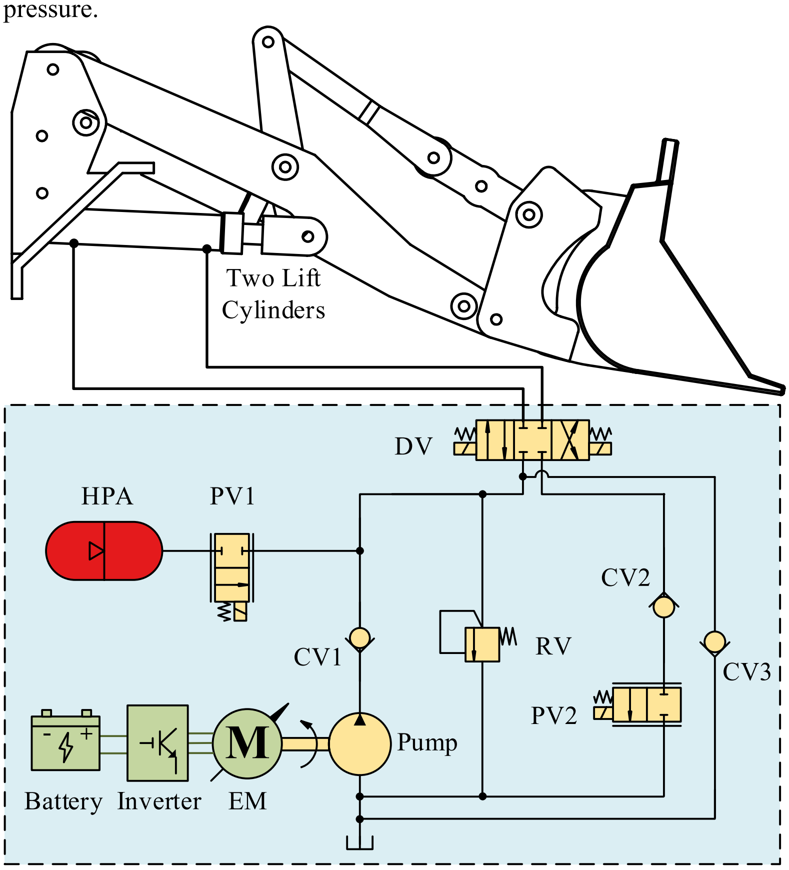


Fig. 1.1. The proposed electro-hydraulic hybrid variable speed drive (EH-VSD) working system

2.2. System Modelling

1) Electric Motor/Generator: The electric motor is modelled using a d–q axis framework, where the direct axis (d) aligns with the rotor flux, and the quadrature axis (q) is orthogonal to it. This empirical model for the permanent magnet synchronous motor (PMSM) captures the motor's dynamic behaviour during rapid acceleration and deceleration and allows for adjustable step sizes in real-time simulations.

According to the generalized form of Ohm's law, the d- axis and q-axis components of the stator voltage space vector, u_d and u_q, are expressed as:

$$\begin{cases} u_d = R_s I_d - \omega_e \psi_q + \dot{\psi}_d \\ u_q = R_s I_q + \omega_e \psi_d + \dot{\psi}_q \end{cases} \tag{4}$$

where R_s is stator winding resistance and ω_e is the angular velocity of the rotor.

The d–q components of the flux linkage, ψ_d and ψ_q, are given by:

$$\begin{cases} \psi_d = L_d I_d + \psi_{pm} \\ \psi_q = L_q I_q \end{cases} \tag{5}$$

where L_d and L_q are stator cyclic inductances along the d-q axis, I_d and I_q are corresponding stator currents, and ψ_{pm} is permanent magnet flux linkage.

The electromagnetic torque, T_{em}, is calculated by:

$$T_{em} = \frac{3}{2} N\left(\psi_d I_q - \psi_q I_d\right) \tag{6}$$

where p is the number of pole pairs.

The dynamic equation of the motor shaft is described by:

$$\left(J_{em} + J_p\right)\dot{\omega_{em}} = T_{em} - T_p - T_f \tag{7}$$

where J_{em} and J_p are the shaft inertia of electric motor and pump, T_p is the torque of pump and T_f is viscous friction torque.

2) Fixed Displacement Pump: The fixed-displacement pump model incorporates the variation of component efficiencies with operating speed and pressure. It determines the output torque and flow rate based on an efficiency map that reflects these dependencies. The shaft torque T_p, and inlet flow rate Q_p, of the pump are given by:

$$\begin{cases} T_p = \dfrac{D_p(p_H - p_L)}{\eta_m^a} \\ Q_p = D_p \omega_p \eta_v^a \end{cases} \tag{9}$$

where D_p is full displacement of pump, p_H and p_L are the high and low pressure sides of the pump, η_m and η_v are mechanical and volumetric efficiencies which are pressure and shaft speed-dependent, a is mode factor of pump, ω_p is the shaft speed of pump and is equal to the electric motor speed $\omega_p = \omega_{em}$.

3) Accumulator: During the loading cycle, both the charging and discharging of the accumulator are relatively short. Therefore, the accumulator is modelled using the isothermal gas law, assuming a constant operating temperature. The pressure of the accumulator, p_{acc}, is given by:

$$p_{acc} = p_0 \left(\frac{V_0}{V_{acc}}\right)^{\gamma} \tag{10}$$

where p_0 is pre-charge pressure, V_0 and V_{acc} are initial and current gas volume and γ is polytropic index of gas.

The current gas volume of the accumulator is determined by the integral of the flow rate over time. The flow rate, Q_{acc}, is considered positive during discharge and negative during charging. The gas volume, V_{gas}, is expressed as:

$$V_{acc} = V_0 + \int Q_{acc}dt \tag{11}$$

The hydraulic state of charge (SOC) of the accumulator, SOC_{acc}, is defined as:

$$SOC_{acc} = \frac{p_{acc} - p_{min}}{p_{max} - p_{min}} \tag{12}$$

where p_{min} and p_{max} are the maximum and minimum allowable accumulator pressure.

4) Proportional Valve: A proportional valve is used to regulate the flow rate from the high-pressure accumulator and another one controls the lowering speed of the lift cylinder. The flow rate across the directional valve, Q_v, is:

$$Q_v = c_q A_v x_v \sqrt{\frac{2|\Delta p|}{\rho}} \tag{13}$$

where c_q is flow coefficient, A_v is throttling area of proportional valve, x_v is the valve opening ratio, Δp is the pressure difference of valve inlet and outlet, ρ is hydraulic fluid density.

5) Hydraulic Cylinder: The dynamic behaviour of cylinder can be described by a set of well-established mathematical equations:

$$\begin{cases} Q_A - A\dot{x_{cyl}} = \frac{V_A}{E_h}\dot{p_A} \\ a\dot{x_{cyl}} - Q_a = \frac{V_a}{E_h}\dot{p_a} \\ p_A A - p_a a - F_{load} - Bv = m\ddot{x_{cyl}} \end{cases} \tag{16}$$

where p_A and p_a are pressure in the piston and rod chambers, A and a are the effective area of piston and rod sides, Q_A and Q_a are flow rate of piston and rod chamber, V_A and V_a are control volumes of piston and rod chambers, E_h is the effective bulk modulus of hydraulic fluid, F_{load} is the external load force on the piston, B is viscous friction coefficient, x_{cyl} is piston displacement and m is equivalent mass of piston.

2.3. Working Mode

The proposed EH-VSD system operates in four working modes: pump-driven lifting mode, hybrid-driven lifting mode, valve-controlled lowering mode, and accumulator charging mode. The overall system operation is coordinated by an energy management strategy (EMS), as illustrated in Fig. 2.2.

(a) Pump-driven Lifting Mode: In this mode, the control strategy integrates feedforward speed estimation with position PI feedback to achieve accurate cylinder motion control. Based on the cylinder velocity in the given loading cycle, the EMS calculates the theoretical rotational speed of the VSD unit, which serves as the feedforward term for the electric motor speed command. In parallel, a position PI feedback controller computes a speed compensation from the position difference between the actual cylinder position and reference given by EMS. The feedforward and feedback components are combined to ensure precise cylinder position control. The baseline VSD system also employs this same control approach, regulating cylinder position through motor speed adjustment.

(b) Hybrid-driven Lifting Mode: In the hybrid mode, the flow rate outputs of the VSD unit and the high-pressure accumulator are determined in advance by the dynamic programming–based optimization method (to be described in the following subsection), and EMS assigns the corresponding reference control signals to each module. The high-pressure accumulator is regulated using proportional control, where the opening of PV1 is determined by the PI controller based on the error between the theoretical and actual flow rates, ensuring accurate control of the accumulator's output power. The VSD unit continues to employ the feedforward and feedback control strategy, with the feedback loop ensuring precise lift cylinder position tracking.

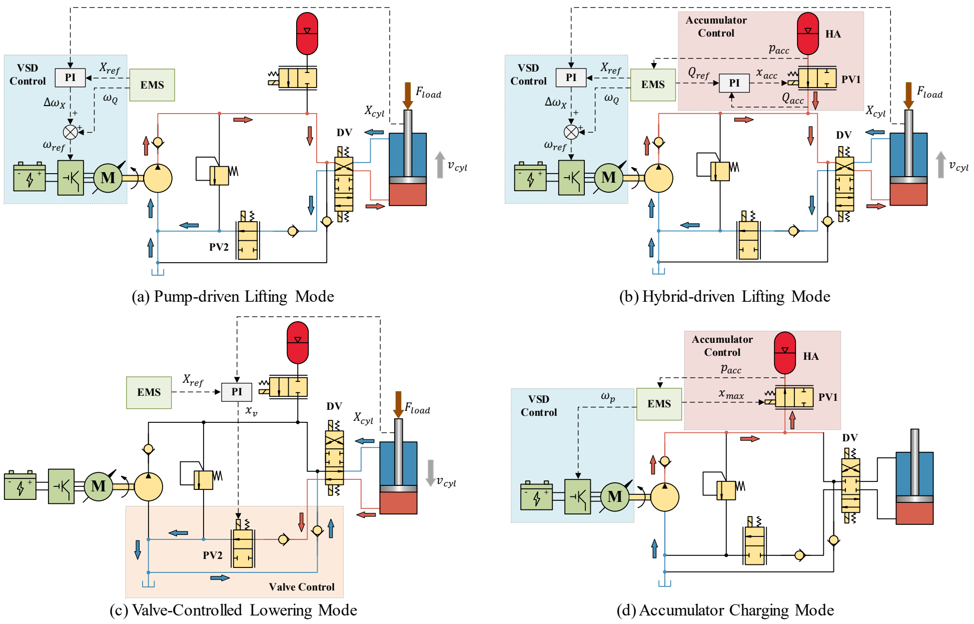


Fig. 2.2. Working modes of the EH-VSD working system

(c) Valve-Controlled Lowering Mode: In this mode, a hydraulic cylinder position PI controller is employed. The PI controller regulates the opening of the proportional valve based on the error between the theoretical position provided by the EMS and the actual actuator position, achieving controlled lowering of the cylinder through outlet throttling. Furthermore, not utilizing the VSD unit for energy recovery in this mode offers additional benefits: (i) the hydraulic pump does not need to operate in bidirectional rotation, so a unidirectional pump can be utilized, thereby reducing component cost, (ii) the electric motor avoids operating in generator mode, which would otherwise cause significant power losses and increase motor temperature, negatively affecting its operating condition.

(d) Accumulator Charging Mode: In this mode, the proportional valve of the accumulator module is kept fully open to avoid additional throttling losses. The EMS regulates the VSD unit speed according to the optimization results obtained from the dynamic programming, ensuring that both the motor and hydraulic pump operate within their high-efficiency regions. Once SOC_acc reaches its maximum value (i.e., the initial state), the proportional valve of the accumulator module is closed, and the VSD unit returns to standby mode.

3. System Control Strategy

3.1. *Overview*

Compared with the VSD working system, the proposed EH-VSD system incorporates two power sources: the VSD unit and the high-pressure hydraulic accumulator. The inclusion of the accumulator provides an additional degree of freedom for system control, and certain parts of the system configuration differ from the conventional design. Consequently, different working modes must be assigned according to the wheel loader's loading cycle. Multiple power sources enable power-split operation within the system. The accumulator not only reduces the installed power requirement but also facilitates optimal system-level control aimed at improving energy efficiency. The power distribution between the VSD unit and the accumulator has a significant impact on both installed power and system energy efficiency, making it necessary to perform optimization of power distribution.

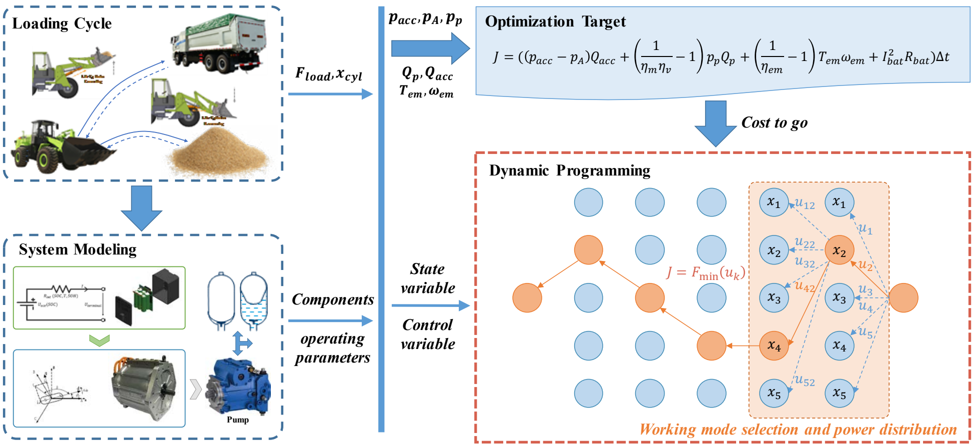


Fig. 3.1. Control schematic of the mode-based control strategy of proposed powertrain

The control strategy and power distribution optimization framework for the proposed EH-VSD system are illustrated in Fig. 3.1. First, the loading cycle of wheel loader are analyzed to determine the control strategy and optimization boundary. Then, based on the loading cycle and the system mathematical model established in section 2, a cost function is formulated to define the optimization objectives. Finally, the dynamic programming is then applied to select the working mode of system and achieve the globally optimal power distribution parameters, thereby maximizing energy efficiency under the minimum installed power constraint.

3.2. *Optimization Method*

Dynamic programming (DP) is commonly used to solve global optimization problems by decomposing them into a series of simpler sub-problems [18, 19]. Under a known loading cycle, DP discretizes the cycle and solves the problem step-by-step, reducing computational complexity by storing and reusing solutions of sub-problems [20, 21].

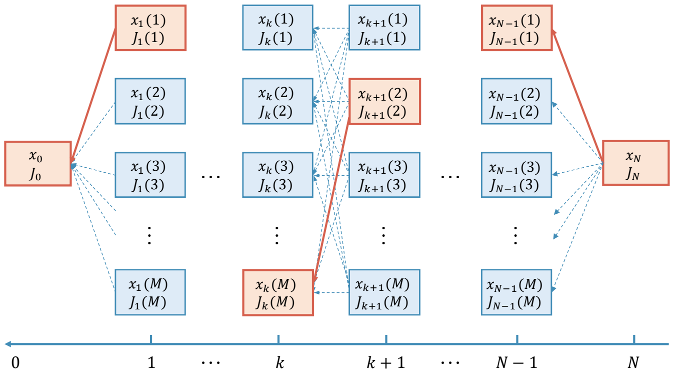


Fig. 3.2. Dynamic programming for the power distribution optimization method

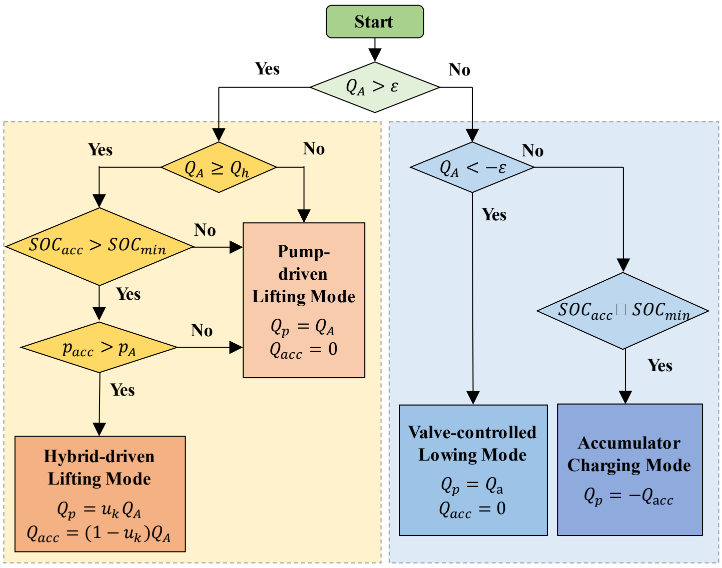


Fig. 3.3. Working mode selection within the dynamic programming

This study focuses on the EH-VSD working system to investigate the optimal power distribution between VSD unit and high-pressure accumulator. The objective is to reduce the installed power while improving overall system energy efficiency. The time horizon is discretized into N equally spaced intervals. Appropriate state and control variables are selected and discretized into an M-dimensional grid. A performance objective function is formulated based on the system's energy losses. Under constraints on initial and terminal states as well as component operational limits, a backward recursion algorithm is used to find the global optimum. Subsequently, a forward pass calculates the power-optimal control inputs.

In addition to the conventional optimal power distribution, a working mode selection strategy is integrated into the dynamic programming framework to ensure proper system operation and reduce the computational load of the DP process. The control logic of this strategy is consistent with that described in Section 2, where one of four operating modes is selected based on the required flow rate of the working system in the loading cycle.

4. SIMULATION STUDY

4.1. Simulation Parameters

The simulation study is conducted on Matlab and Amesim platforms. Matlab is used for control strategy and optimization method, while Amesim is applied for component model verification and simulation operation. The main parameters of the proposed EH-VSD system are designed according to the existing electric wheel loader working system with all components commercially available. The battery pack is a 456 Ah lithium iron phosphate type, whose open-circuit voltage and internal resistance vary with battery SOC. When the SOC decreases, the battery voltage drops while the internal resistance rises.

Table 3.1

Main parameters of proposed EH-VSD system

	Property	Value	Unit
Battery	Normal capacitance	456	Ah
	Normal voltage	618	V
	Normal Initial resistance	20	mΩ
Electric motor	Max. speed	3000	rpm
	Max. torque	450	Nm
Hydraulic pump	Geometric displacement	100	cc/rev
	Max. speed	3000	rpm
	Max. pressure	30	MPa
Hydraulic accumulator	Volume	25	L
	Max./Min. pressure	32/12	MPa
	Efficiency	85%	\
Proportional valve	Valve coefficient	0.7	\
	Natural frequency	80	Hz
Hydraulic pipeline	Length	3	m
	Diameter	20	mm
	Relative roughness	0.002	\
	Hydraulic fluid viscosity	46	mm^2/s
Hydraulic cylinder	Diameter of piston	150	mm
	Diameter of rod	90	mm
	Piston stroke	815	mm
	Viscous friction coefficient	2000	N/(m/s)

Permanent magnet synchronous motor (PMSM) is adopted, with maximum speed and torque limited to 3000 rpm and 450 Nm respectively. A unidirectional fixed-displacement pump of 100 cc/rev is employed with a maximum pressure of 30 MPa, and a 25 L high-pressure accumulator operates within pressure range of 12–32 MPa.

The electric motor–pump unit (VSD unit) used in this study adopts efficiency maps obtained from manufacturer data and test bench measurements. The operating efficiency depends on motor torque (related to pump pressure) and rotational speed. Therefore, optimizing the operating points of the VSD unit can effectively improve system energy efficiency.

4.2. Simulation Results and Performance Comparison

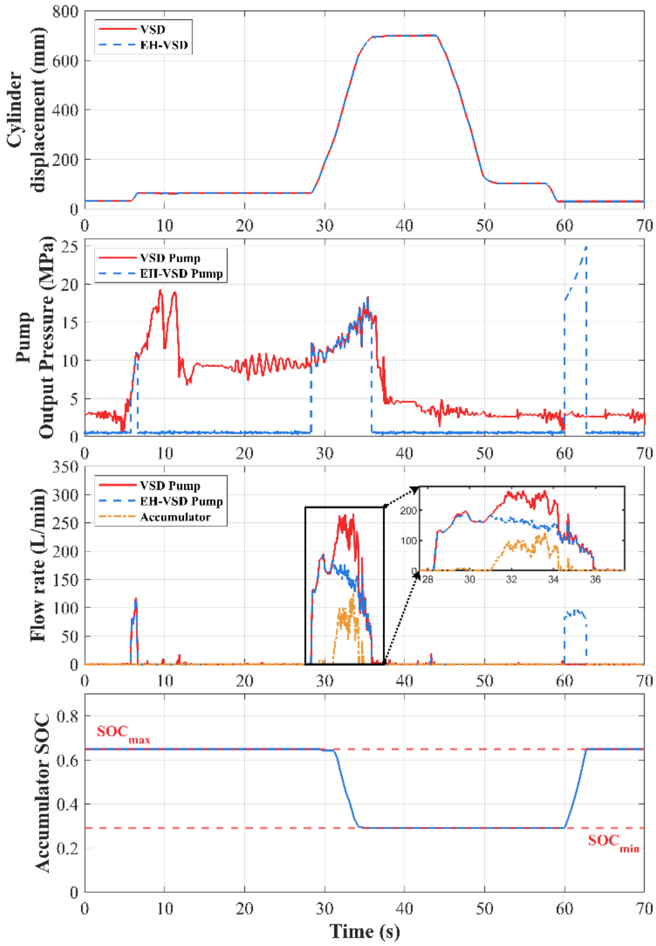


Fig. 4.1. Comparison of hydraulic components performance between systems

The performance of hydraulic components in both the baseline VSD system and the proposed EH-VSD system is shown in Fig. 4.1. In both cases, the hydraulic cylinders accurately follow the reference signal to complete the loading task. In VSD system, the pump outlet pressure remains nearly consistent with the load pressure. In the EH-VSD system, due to the check valve at the pump outlet, pressure is generated only when the pump works, and it closely matches the load pressure. After the loading cycle, the pump also charges the accumulator, during which outlet pressure follows the accumulator pressure.

The flow rate output highlights the differences between the two systems. In the VSD system, the hydraulic pump alone supplies the flow required for cylinder lifting. In contrast, the EH-

VSD system combines the outputs of the pump and accumulator, where the pump provides a nearly constant flow and the accumulator compensates for the remaining demand, thereby reducing the pump's power output. During cylinder lowering, the VSD and EH-VSD system adopt throttling, eliminating the need for pump operation. The accumulator SOC remains within its operating range, starting from a maximum of 0.65, decreasing to 0.3 after the hybrid lifting mode, and then being recharged by the VSD unit to its initial state in preparation for the next cycle.

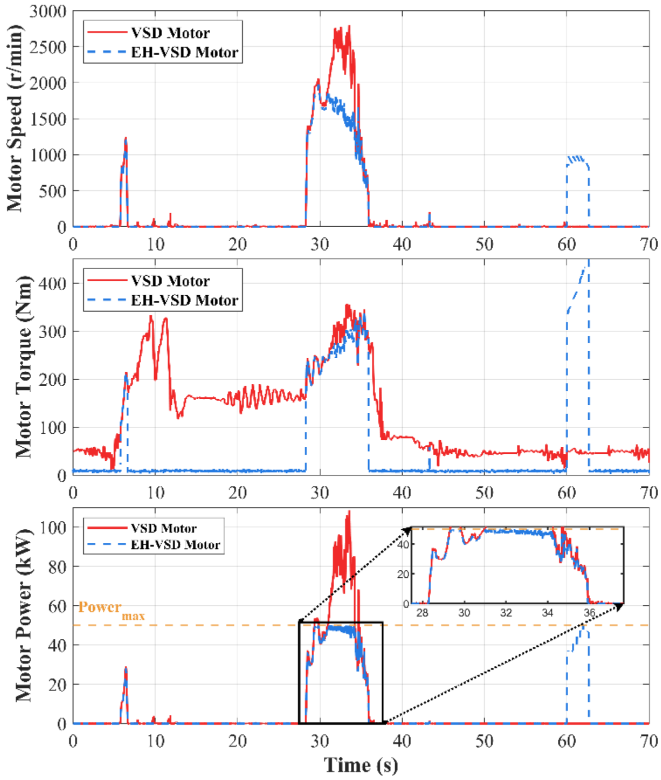
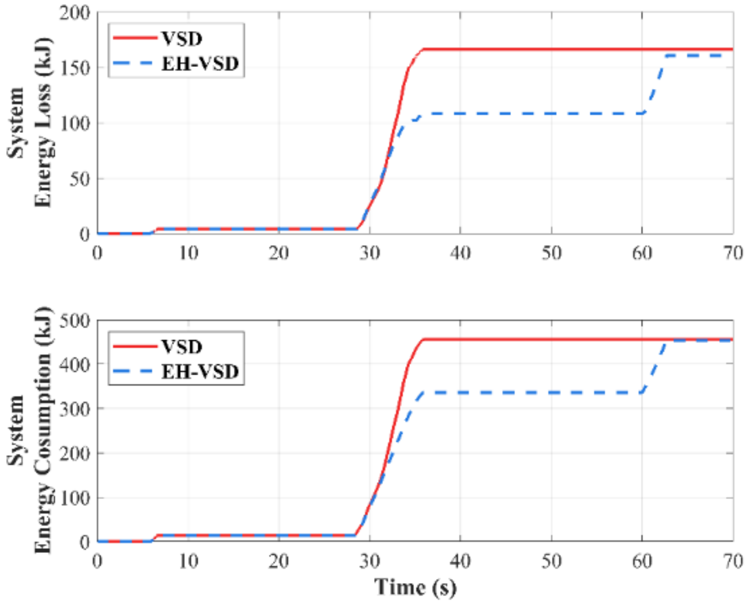


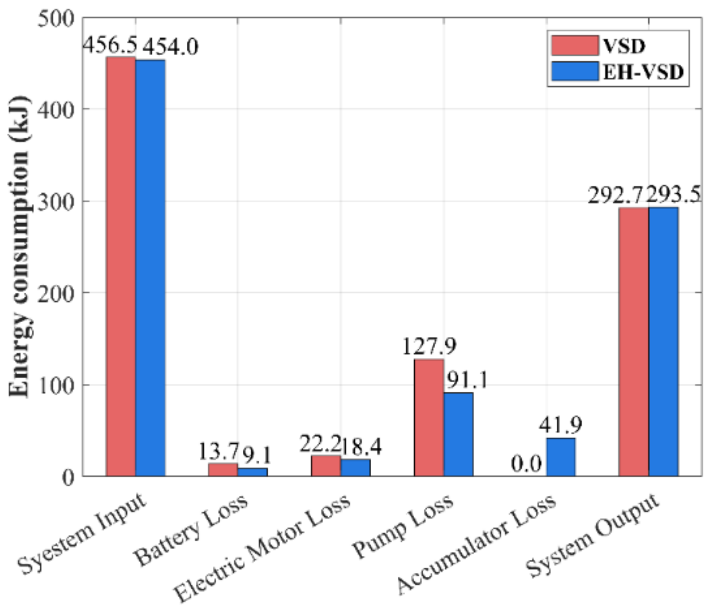
Fig. 4.2. Comparison of electric motor performance between systems

Fig. 4.2. compares the motor performance of the two systems. The motor speeds are nearly identical, except that the EH-VSD shows a lower speed during lifting since part of the flow is supplied by the accumulator. The motor torque follows a similar trend to the pump pressure, consistent with Eq. (7) and (9). The motor power of the EH-VSD system remains below the power limit of 50 kW in both lifting and charging modes, while the VSD system must supply the entire load independently, reaching a peak power of 110 kW. This represents a 54.5% reduction in installed power, confirming the feasibility of the proposed strategy in which the motor provides average power and the accumulator delivers peak power.

Fig. 4.3 compares the energy consumption of the EH-VSD and VSD systems to evaluate energy efficiency. Fig. 4.3 (a) shows system energy loss and consumption during one loading cycle. In the lifting mode, the EH-VSD system exhibits lower energy loss, attributed to the optimized power distribution strategy. During accumulator charging, EH-VSD incurs additional loss from the VSD unit, bringing the total loss close to that of the VSD system. The final energy consumption of both systems is nearly identical, and VSD system is even higher.



(a) System energy loss and consumption



(b) Energy consumption of components

Fig. 4.3. The energy consumption comparison between VSD and EH-VSD system in one loading cycle

Fig. 4.3 (b) illustrates the component-level energy losses, including battery, motor, pump, accumulator, and other hydraulic elements (merged into pump loss). The VSD system requires higher input energy than the EH-VSD system. The EH-VSD system exhibits lower losses in the battery, motor, and pump, thereby improving overall efficiency. Although EH-VSD has accumulator charging/discharging and throttling loss, these have been minimized through optimization.

Table 4.1

Performance comparison between VSD and EH-VSD systems

	VSD	**EH-VSD**	**Comparison**
Installed Power	110 kW	50 kW	**-54.5%**
Energy Consumption	456.5 kJ	454.0 kJ	**-0.6%**
Energy Efficiency	64.1%	64.6%	**+0.5%**

As shown in Table 4.1, the performance of the two systems is compared for a single loading cycle. The proposed EH-VSD system reduces installed motor power by 54.5%, energy consumption by 0.6%, and improves energy efficiency by 0.5% compared with the VSD system, significantly enhancing overall operational performance. The EH-VSD system achieves a significant reduction in installed power while maintaining a high energy efficiency comparable to that of the VSD system, effectively avoiding substantial throttling losses.

5. CONCLUSIONS

In this paper, an electro-hydraulic hybrid variable speed drive system (EH-VSD) is proposed to downsize the electric motor of electric wheel loader working function. A high-pressure accumulator in parallel configuration assists the VSD unit under high load condition, to reduce system installed power. An energy management strategy based on the dynamic programming is developed to ensures the VSD unit operates within its high-efficiency region, improving the energy efficiency of the system. The comparison between proposed system and baseline system, and comparative simulation of different accumulator parameters are conducted in terms of system performance, installed power and energy efficiency.

Simulation results show that the installed power of EH-VSD system reduces by 54.5% compared to VSD system (from 100 kW to 50 kW). The EH-VSD system achieves a significant reduction in installed power while maintaining a high energy efficiency comparable to that of the VSD system, effectively avoiding substantial throttling losses.

The proposed EH-VSD system significantly reduces the installed power while maintaining energy efficiency. However, the complexity of system will increase due to the addition of components, heightened requirements for electro-hydraulic control precision, and the incorporation of additional control algorithms. Furthermore, this paper has only conducted simulation studies for a single cycle. Although the methodology can be applied to other scenarios, further experimental validation across additional cycles is required to demonstrate the universality of system and control strategy.

Future work will focus on three aspects: 1) optimizing the system configuration to realize boom energy regeneration; 2) optimizing accumulator parameters to further improve energy efficiency; and 3) conducting experiments on a test bench or machine to evaluate the actual performance.

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