[UCI]I804:48009-200000284592

공학박사 학위 논문

굴착기 유압식 스윙 시스템의 구조 및 제어 전략 개발

STRUCTURE AND CONTROL STRATEGY DESIGN OF NOVEL HYDRAULIC HYBRID SWING SYSTEM OF EXCAVATOR

울산대학교 대학원

기계자동차 공학과

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STRUCTURE AND CONTROL STRATEGY DESIGN OF NOVEL HYDRAULIC HYBRID SWING SYSTEM OF EXCAVATOR

A thesis submitted in partial fulfillment of the requirement for the Degree of

Doctor of Philosophy to the School of Mechanical and Automotive

Engineering, University of Ulsan, Korea

By

YING XIAO YU

December 2019

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지도교수 **안경관**

이논문을 공학박사 학위 논문으로 제출함

2019 년 12 월

울산대학교 대학원

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STRUCTURE AND CONTROL STRATEGY DESIGN OF NOVEL HYDRAULIC HYBRID SWING SYSTEM OF EXCAVATOR

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2019 년 12 월

Acknowledgements

During the time of research and thesis writing, I got so much help from many excellent people. Hence, the thesis can be finished successfully.

Firstly, I appreciate the support and help of my advisor, Prof. Kyoung Kwan Ahn. During my 5 years research of PhD courses, my advisor shared his knowledge with me and guide me to improve my research ability dramatically. He supported me in my research unsparingly and provided the best research environment to me. With his guideline and help, I finish the work of this thesis smoothly.

Besides my advisor, I would like to thank to Prof. Lee, Byung Ryong, Prof. Yang, Soon Young, Prof. Ha, Cheol Kuen and Prof. Truong, Dinh Quang for their insightful comments and encouragement, but also for the hard question which incented me to enhance my research from various perspectives.

I also thank the help of my lab members. When I face the problem in my research and ask help from the lab members, they always help me to solve the problem kindly and share their experience to me. Without their help, I cannot finish my research and this thesis.

Last but not the least, I would like to express my thanks to my family: my parents and my wife for supporting me during my Ph.D study and understanding me all the time.

Ulsan, December 2019

Ying Xiao Yu

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Abbreviations

HMD	Hydraulic motor displacement
ESU	Energy storage unit
FCV	Flow control valve
CCHF	Combined control of hydraulic motor and flow control valve
SOC	State of charge

Abstract

This thesis presents a novel energy saving swing system of hydraulic excavator, in which hydraulic hybrid technology is utilized. Two independent hydraulic accumulators are used as the energy storage unit to store the regenerated energy, and several additional control valves are installed in system. The combined control of hydraulic motor displacement and flow control valve, and the variable accumulator control strategy are proposed for the improvement of energy regeneration efficiency. The structure and control strategy of energy reuse are studied to reuse the stored regenerated energy. The test bench is built in lab and experiments of energy regeneration and energy reuse are conducted. As a result, the combined control of hydraulic motor displacement and flow control valve improves 64% of regenerated energy and reduces the swing part oscillation. The variable accumulator control strategy improves 27% of the regenerated energy maximally. The experiment results verify that the energy regeneration efficiency of the proposed system is between 23% and 56% in different conditions. Consequently, the average energy saving efficiency is 26.7%

Firstly, the electric hybrid excavators and hydraulic hybrid excavators are discussed. The key components and existed control strategies of energy regeneration and energy reuse are introduced. The advantages and disadvantages of each structure of hybrid hydraulic excavators are analyzed.

Secondly, a novel energy saving swing system of excavator is proposed. The design of the system and test bench parameters setting are discussed. In the proposed system, two independent hydraulic accumulators are used as the energy storage unit, and several control valves are set up to regulate the flow in energy regeneration mode and energy reuse mode.

Thirdly, the combined control of hydraulic motor displacement and flow control valve, and variable accumulator control strategy are proposed to improve the energy regeneration efficiency. Then the energy reuse control strategy is proposed to reuse the stored regenerated energy.

Finally, the experiment of the proposed system is conducted, and the experiment results are analyzed. The energy regeneration efficiency is improved with the proposed control strategy. Consequently, the proposed system could reduce the energy consumption obviously.

Chapter 1. INTRODUCTION

1.1 Overview

Recently, energy crisis and environmental pollution have become serious problems in the world rang[1]–[3]. The manufacturing and construction sector accounted for an average of 12.6% of the world air pollutions (in 2006). The energy saving of construction machines, especially the hydraulic excavator is important[4]–[7].

Hybrid technology is an effective way to reduce the energy consumption of hydraulic excavator[8]–[12]. The battery, supercapacitor, flywheel, and hydrogen storage are newly-developed to store energy in hybrid system[13]–[15]. The flywheel can only store small amount of energy. Flow batteries and hydrogen energy storage are in the developing phase[16]. Battery and supercapacitor have high energy density and long lifetime. The battery and supercapacitor have been utilized in the commercial electric hybrid vehicles for several decades. The low fuel consumption and good performance of battery are verified by the commercial production, such as the Prius of Toyota. In recent years, there are many researches about the electric hybrid excavator, in which the battery and supercapacitor are used as the energy storage[17]–[19]. In another aspect, the hydraulic accumulator is an energy storage unit, which is used in hydraulic system. By using a hydraulic accumulator, the hydraulic hybrid system is also a method to save energy[20]. Both electric hybrid excavator and hydraulic hybrid excavator could regenerate the protentional energy and kinetic energy of the actuators[21]. Then, the regenerated energy can be reused to reduce the total energy resumption.

The hybrid electric -hydraulic excavator was researched to regenerate the protentional energy of boom[22]. The hydraulic motor and generator were set up in the return line of boom system. When boom moves down, the fluid from the head chamber of cylinder flows to the hydraulic motor. The hydraulic motor drives the generator to regenerate the protentional energy of the boom. The experiment results shown that the energy regeneration efficiency was mainly between 0.26 and 0.33. The energy regeneration of electric forklift system was researched to realize a 54% of energy saving efficiency[23]. In this system, the key component is the pump/motor, which can work as a pump to drive the system and can work as a hydraulic motor for energy regeneration. The accumulator can also be used in the electric hybrid hydraulic system, which is called accumulator-motor-generator system[24]. In this system, the protentional energy was saved in accumulator in boom down mode. Then, the generator was driven by the flow from the accumulator, even if the system worked in boom up mode. Hence, the working time of generator can be extended. In this process, the working efficiency of generator was improved. The simulation results showed that the energy regeneration efficiency was 41%. The experiment results showed that the recovery efficiency was 39%.

Based on above analysis, the hybrid electric- hydraulic excavator can save much energy. However, the components of the battery, supercapacitor, additional hydraulic motor and pump/ motor increase the cost of the system. The multiple energy conversions lead to low energy saving efficiency. The hydraulic hybrid system could balance the cost of system and energy saving efficiency. The hydraulic accumulator is used to store the regenerated energy with low cost.

Energy regeneration of swing system of excavator was researched by using a hydraulic accumulator[25]. Two concepts of system were analyzed, in which the variable displacement hydraulic pump/motor and additional pump was equipped in the system respectively. However, the additional components increase the cost of system and only one condition was considered in the simulation. The energy regeneration of swing system was researched with different hydraulic motor displacement (HMD) and accumulator[26]. The simulations results verified that the HMD and accumulator size affected the regenerated energy. In the real swing system, the accumulator pressure, swing part speed, deceleration time and inertia are needed to be considered. The energy regeneration efficiency and system performance need to be verified by experiment.

To improve the energy regeneration efficiency and system performance, the hydraulic transformer can be used in the hydraulic system[27], [28]. The low-pressure source could charge the high- pressure part by using the hydraulic transformer. Hence, the accumulator pressure cannot affect the regenerated energy and the system performance[29]–[31]. The energy regeneration of IMV system with hydraulic transformer was researched[32], in which the energy working condition was optimized and energy consumption of system was decreased. The accumulator pressure was considered in these researches, but the other factors were not considered. Furthermore, the hydraulic transformer is expensive and complex, and no commercial product is available to be used in the hydraulic excavator.

Hence, the electric hybrid excavator could reduce the energy consumption, which has verified by experiments. But the additional components increase the cost of the system. The hydraulic accumulator is cheap and easy to set up in the hydraulic system. The hydraulic hybrid system can reduce the energy consumption in a cheap way, without using additional components, such as pump/motor and hydraulic transformer. However, there are some factors should be considered, such as accumulator pressure, deceleration time, swing part speed and inertia. Both the energy regeneration and system performance should be considered.

1.2 Research objectives

The main target of this paper is reducing the energy consumption of the swing system of excavator. To solve this problem, this thesis has been focused on following contents: the design of the proposed hydraulic hybrid swing system, the control strategy design, and experiment verification. The specific subjects of the contents are as follows:

Firstly, a novel hydraulic hybrid swing system is proposed by using the hydraulic accumulators. The components and working modes of the system are introduced. The test bench is built by using a flywheel instead of the upper structure of the excavator. Then, parameters setting of the flywheel is discussed.

Next, the control strategy design is presented. The hydraulic motor and flow control valve (FCV) are the key components to be controlled in energy regeneration mode. The combined control of HMD and FCV and variable accumulator control strategy are proposed to improve the energy regeneration efficiency and reduce the swing part fluctuation. In energy reuse mode, the control strategy of the system is also discussed and designed.

Lastly, the energy regeneration efficiency and energy saving efficiency are evaluated by experiments. The energy regeneration efficiencies are tested in different conditions of deceleration time, flywheel speed, and inertial accumulator pressure. The energy saving efficiencies are tested with multi cycles of working.

1.3 Limitation of the dissertation

In this study, the testbench is built with some limitations as follows:

- There are only two kinds of inertia of flywheel can be chosen in the test bench.
- The mechanical brake is not installed in the test bench. Hence, the combination control of mechanical brake and hydraulic brake cannot be tested.

1.4 Dissertation outline

The remainder of this dissertation is organized as follows:

Chapter 2 reports the current research of the hybrid hydraulic excavator.

Chapter 3 presents the configuration of the proposed hydraulic hybrid swing system. The system design, working principle and test bench design are discussed.

Chapter 4 reports the control strategy design of the proposed system. The control strategy of energy regeneration and energy reuse are presented.

Chapter 5 introduces the experiment verification of the system. The energy regeneration efficiency and energy saving efficiency are tested separately. Then the experiment results are analyzed.

Chapter 6 presents the conclusions and proposes the future works.

Chapter 2. HYDRAULIC HYBRID EXCAVATOR STRUCTURE

Hybrid technology is an effective method to reduce the energy consumption of hydraulic excavator. Over the years, several hybrid excavators are researched. In general terms, the hybrid hydraulic excavators can be classified into two types: electric hybrid excavators and hydraulic hybrid excavators. A description of each term is presented as below:

2.1 Electric hybrid excavator

The electric hybrid hydraulic excavator uses the battery or supercapacitor as the energy storage unit (ESU). The protentional energy of actuators can be regenerated into electric energy and saved in the ESU through the generator, in which this process is called energy regeneration. Another important part of electric hybrid hydraulic excavator is energy reuse, in which the electric motor is used to drive the main pump or the actuators to reduce the energy consumption of the engine. In this session, the energy regeneration and energy reuse will be discussed separately.

2.1.1 Energy regeneration system:

The energy regeneration system of electric hybrid hydraulic excavator consists of hydraulic motor, generator, inverter, ESU and additional control valves. The typical utilization of energy regeneration on boom system of excavator is shown in Fig. 2.1. When the boom moves down, the directional valve connects the head chamber of boom cylinder to the hydraulic motor. The fluid of the head chamber of the cylinder flows to the hydraulic motor. Then, the hydraulic motor drives the generator to generate electric energy. In this process, the protentional energy of the load, and the boom itself converts to electric energy through the hydraulic motor and generator. Finally, the electric energy is stored in the ESU.

The key components of energy regeneration system are the hydraulic motor, generator and ESU. The fixed displacement of hydraulic motor is widely researched in the energy regeneration system with cheap price. But the generator cannot always work in high efficiency range. The generator efficiency is a variable based on different speed and torque. Based on the joystick signal, the required flow rate of the head chamber of the cylinder is decided. Then the generator speed is controlled to ensure the required flow rate. The torque of the generator is decided by the load of the boom system. In real excavator, the load is a variable. The speed and torque of generator is decided by the required flow rate and load of the system. Hence, the generator cannot keep working in high efficiency range with a fixed hydraulic motor.

In order to improve the energy regeneration efficiency, the variable hydraulic motor is applied in the energy regeneration system, shown in Fig.2.2. The variable hydraulic motor could adjust the working condition of the generator with different speed and torque. The efficiency of the hydraulic motor is also a variable based on different flow rate, pressure and displacement. Hence, the global efficiency of both hydraulic motor and generator can be improved to control HMD. However, the control of the system is complex, and the cost of the system is increased furthermore.

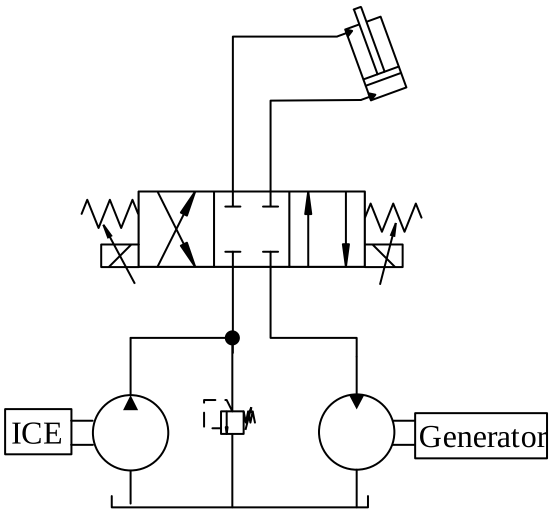

Fig. 2.1 *Typical energy regneration boom system*

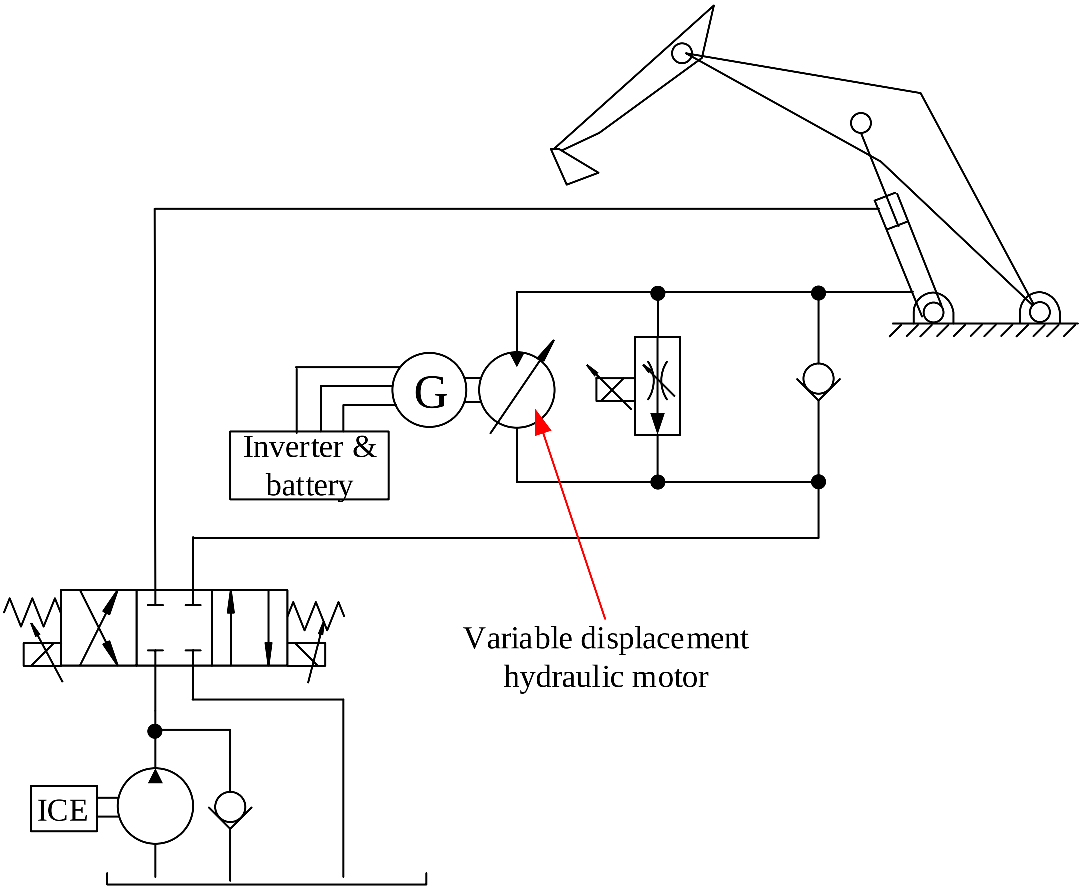

Fig. 2.2 *Energy regeneration boom system with variable hydraulic motor*

The generator parameter setting is also important in the energy regeneration system. The generator efficiency is changed based on different speed and torque, which is analyzed above. An efficiency map of the generator is shown in Fig. 2.3 as an example. The area denoted by red curve represents the high efficiency range of the generator. No matter what kind of hydraulic motor is used in the system to drive the generator, the generator power setup is very important. Based on the load range of the excavator, the torque range of generator can be decided. The speed range of generator can be chosen based on the velocity range of the cylinder. Hence, the generator parameters can be chosen to make the high efficiency range of generator matches most of the working conditions of system. Finally, the energy regeneration efficiency of the system can be improved.

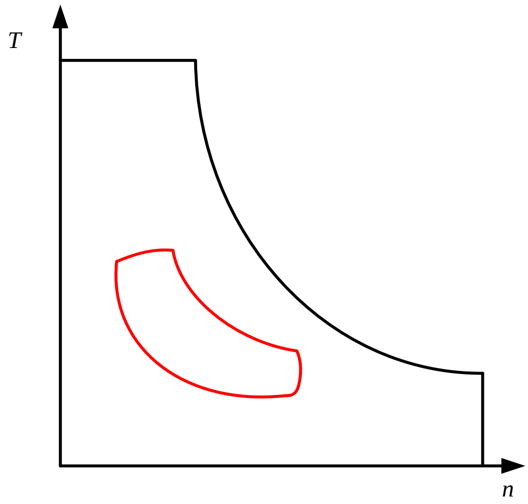

Fig. 2.3 *Efficiency map of generator*

The battery and supercapacitor are common ESU in the energy regeneration system. The battery is widely used in the commercial electric hybrid vehicles. In recent years, the power density and life are improved, and the cost are decreased. Different types of batteries are introduced below.

- Zn-C battery:

Zn-C batteries have a low production and watt-hour cost. Zn-C batteries are reliable and have a moderate shelf life. But the Zn-C batteries disadvantages include low energy density, poor leakage resistance, and voltage drop with discharge[33].

- Lithium primary cells:

Lithium cells have high cell voltage, flat discharge, long life, wide operating temperature range and good power density[34].

- Lead-acid batteries:

Lead-acid is widely used in industry. The lead-acid batteries have low cost, good performance in varying temperatures, high voltage and good charge retention. However, the lead-acid batteries have low cycle life, limited energy density and difficulty in down-scaling[35].

- Lithium-ion batteries:

Lithium-ion batteries are high storage efficiency, long cycle life, high charge/discharge efficiency and high energy density. Hence, the Lithium-ion batteries are applied in hybrid system, such as the electric hybrid vehicles of Toyota.

- Nickel-metal batteries:

Nickel- metal batteries have high energy density, good charge retention, long cycle life and rapid charging. The Nickel- metal were used in electric vehicle[36]. But, the disadvantage of the Nickel- metal batteries are low specific power, and bad performance at low temperature.

- Nickel-cadmium batteries:

The advantage of Nickel-cadmium batteries consists of long cycle life, durability, good charge retention, excellent long-term storage, low maintenance, and flat discharge. The disadvantages are low energy density and high cost[37].

- Nickel-zinc batteries:

The Nickel- zinc batteries has lower cost than the Lithium- ion batteries. This battery has high specific power, high efficiency, and low impact on the environment. However, the zinc is a self-corrosive material[33].

The batteries of electric hybrid system should have long cycle life, because the hybrid system should have the same life of the construction machine. The high charge/ discharge efficiency is necessary, because the efficiency of the hybrid system is very important. Cost of the battery needs to be considered, because the hybrid hydraulic excavator is a commercial product. The efficiency of the battery is also a very important point. One efficiency map of battery is shown in Fig.2.4[38].

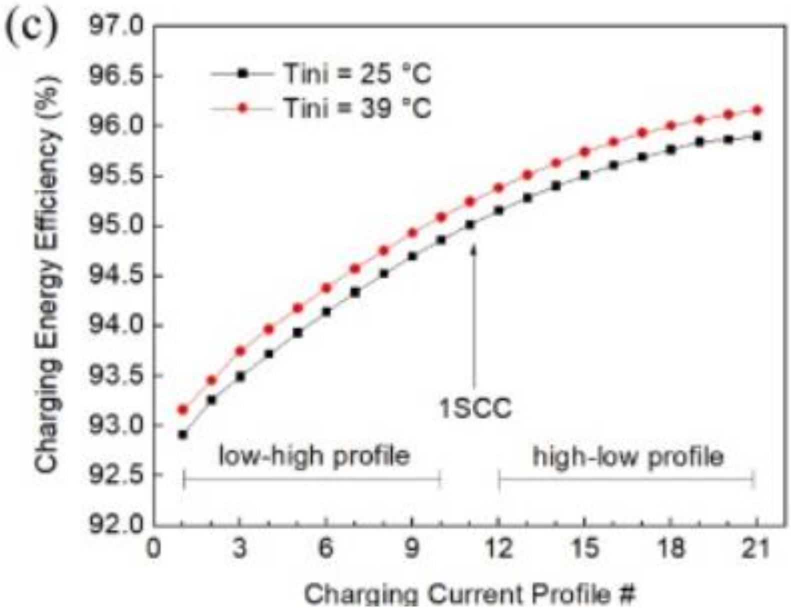

Fig. 2.4 *Efficiency of battery*

In Fig.2.4, the efficiency of the battery is changed with different charging current and temperature. Hence, the current of system should meet the high efficiency rang of the battery.

The supercapacitor is also widely used in electric hybrid system as an ESU. The supercapacitor comprises a pair of conducting plates separated by a dielectric, shown in Fig. 2.5. There are three types of capacitor[39].

- Electrostatic capacitor

The electrostatic capacitor is shown in Fig. 2.5 (a). A pair of conductors separated with a dielectric such as air.

- Electrolytic capacitor

Electrolytic capacitor is shown in Fig. 2.5 (b). The thinner and higher dielectric constant dielectric. The more energy can be stored than that of electrostatic supercapacitor.

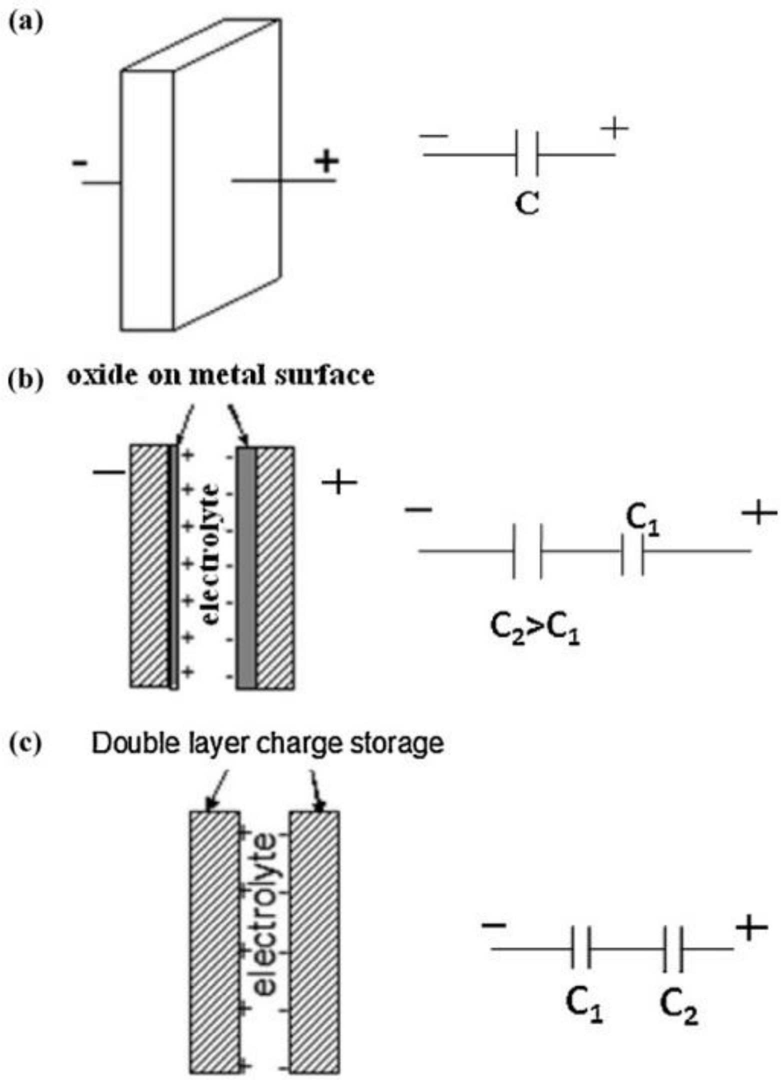

Fig. 2.5 *Structure of capacitors*

- Double-layer capacitor

Double-layer capacitor is shown in Fig. 2.5 (c). This capacitor can store much more energy than the electrostatic capacitor and electrolytic capacitor. This capacitor is referred to as supercapacitor.

The energy density and power density of supercapacitor is much higher than the battery. The supercapacitor has longer charge/ discharge cycles. The supercapacitor can afford high frequency charge/ discharge. Hence, it is suitable for energy regeneration in hybrid system. But, the cost of the supercapacitor is higher than that of the battery.

The supercapacitor and lithium ion battery can be used together in the electric hybrid system. The supercapacitor is used to regenerate the energy of actuator to afford high frequency charge and discharge. The battery is used as the main ESU, which is charged and discharge with low current.

2.1.2 Energy reuse system:

The key component of energy reuse system is electric motor, which can be used to drive the actuator directly or to assist the engine to drive hydraulic pump to reduce the output power of engine. In the system with electric motor and engine, the system can be classified into two types: series hybrid excavator and parallel hybrid excavator. In this chapter, the energy reuse systems of series hybrid excavator and parallel hybrid excavator are discussed separately. Furthermore, the electric drive system is also introduced.

- Series hybrid excavator:

In series hybrid excavator, the generator is connected to the engine and the electric motor is connected to the main pump. The structure of series hybrid system is shown in Fig.2.6. When the system operates, the engine drives the generator to generate electric energy, which will be transfer to the inverter. The inverter combines the electric energy from the generator and the ESU, and transfers the electric energy to the electric motor. Finally, the electric motor drives the hydraulic pump to operate the actuator. The energy flow is shown in Fig. 2.7. In this process, the regenerated energy in ESU is reused. Hence, the energy consumption from the engine can be reduced.

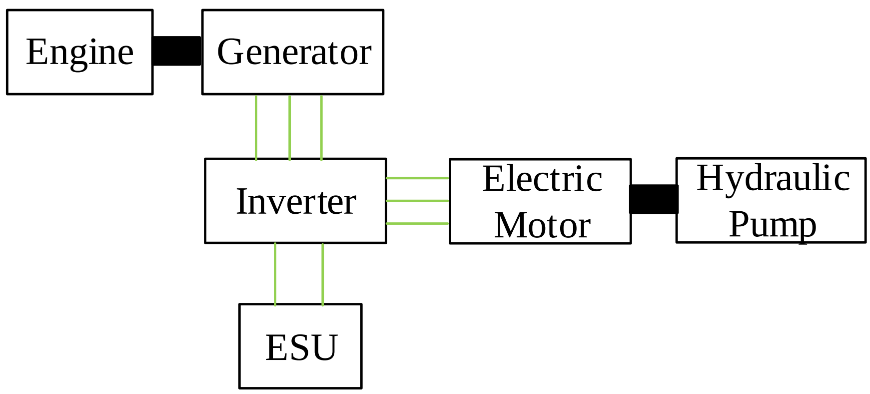

Fig. 2.6 *Structure of series hybrid system*

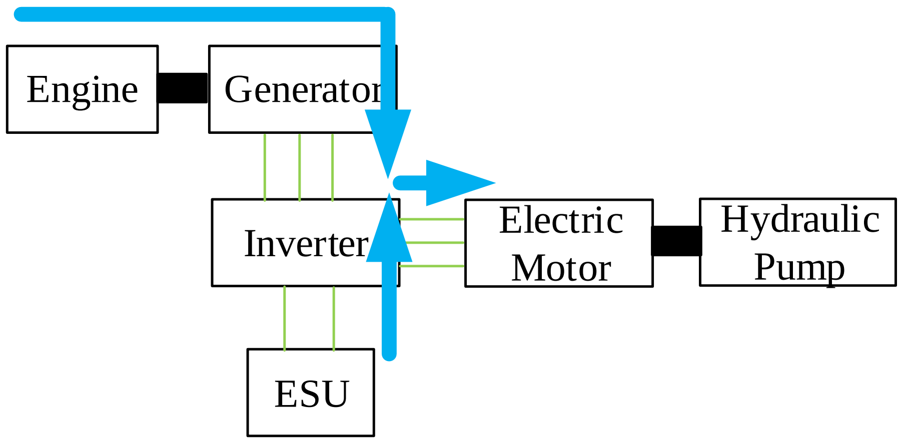

Fig. 2.7 *Energy flow of series hybrid system (1)*

The advantage of this structure is that the engine is decoupled form the pump as well as the load. Hence, the load may not affect the engine working condition directly. The engine can always work in high efficiency range with a constant power output. The engine efficiency map is shown in Fig. 2.8, in which the blue area is the highest efficiency range of engine. Normally, the high efficiency rang is located at area with high torque and middle speed.

If the required power of the system is larger than the engine output power, the ESU will provide additional power to the system. If the required power of the system is smaller than the engine output power, the extra energy will be charged into the ESU through the inverter. The energy flow can be seen in Fig. 2.9. Hence, the ESU may compensate the engine output power, based on the system requirement. The engine working points can also be adjusted, which will be discussed in the control strategy part.

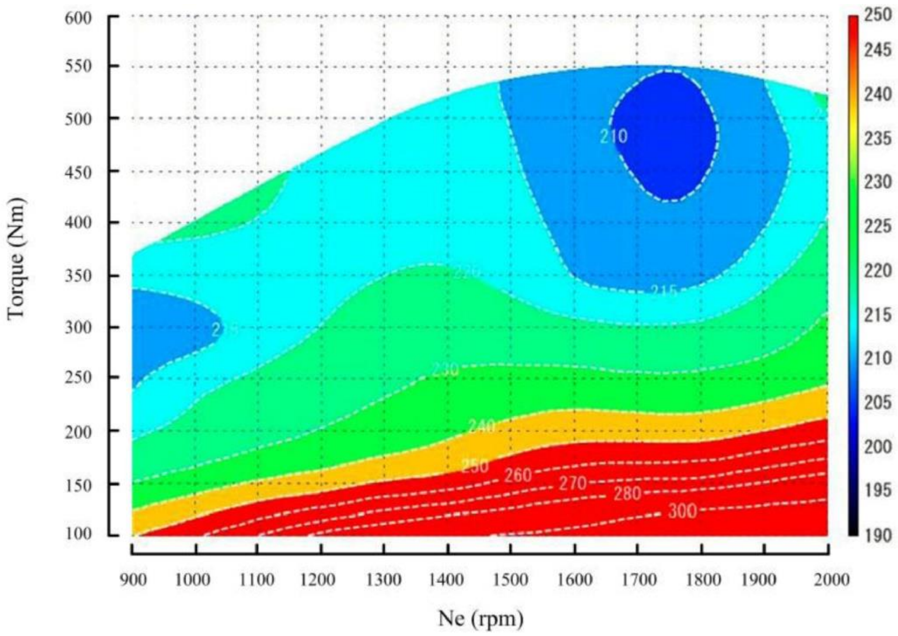

Fig. 2.8 *Engine efficinecy map[40]*

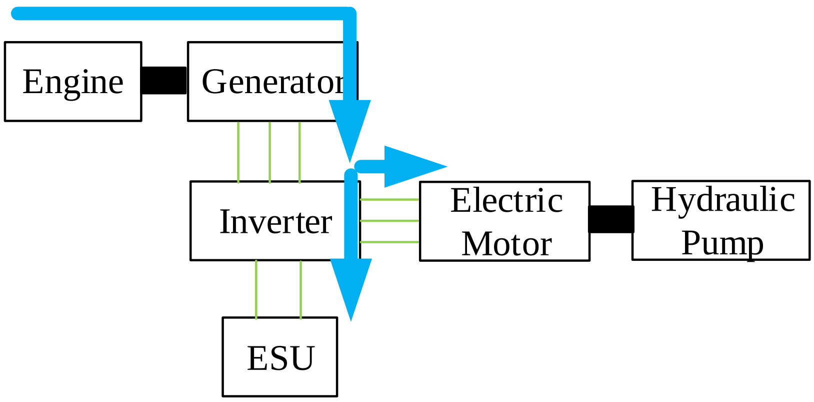

Fig. 2.9 *Energy flow of series hybrid system (2)*

Hence, in the series hybrid system, the ESU not only can provide energy, but also can save the additional energy.

- Parallel hybrid excavator:

In parallel hybrid excavator, the engine, electric motor and hydraulic pump are connected coaxially. The structure is shown in Fig. 2.10. When, the main pump needs energy to run the actuator, the engine and electric motor drive the main pump together. In this process, the electric motor provides additional torque to assist the engine and reduce the energy consumption of the engine. The electric motor uses the regenerated energy, which is stored in ESU. Hence, the regenerated energy is reused in this process. The energy flow is shown in Fig. 2.11.

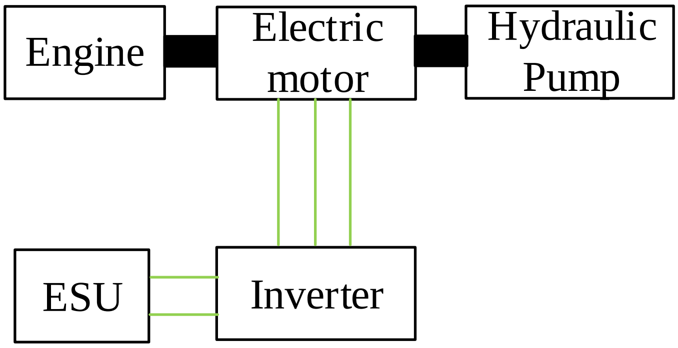

Fig. 2.10 *Structure of parallel hybrid system*

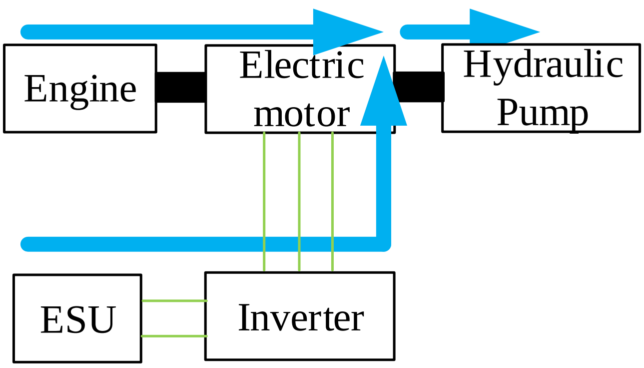

Fig. 2.11 *Energy flow of parallel hybrid system*

In some parallel hybrid excavators, the electric motor can also work as a generator, which is shown in Fig.2.12. When the system operates, the motor/generator can provide energy to assist the engine or generate energy to store it in the ESU. If the required power of hydraulic pump is larger than the common value, the motor/generator will output power to assist the engine. If the required power of hydraulic pump is lower than the common value, the motor/generator will work as a generator to generate electric energy, which is saved in the ESU. Hence, part of the energy of engine is stored in the ESU. The energy flow is shown in Fig. 2.13. Finally, the engine working condition can be stable with high efficiency.

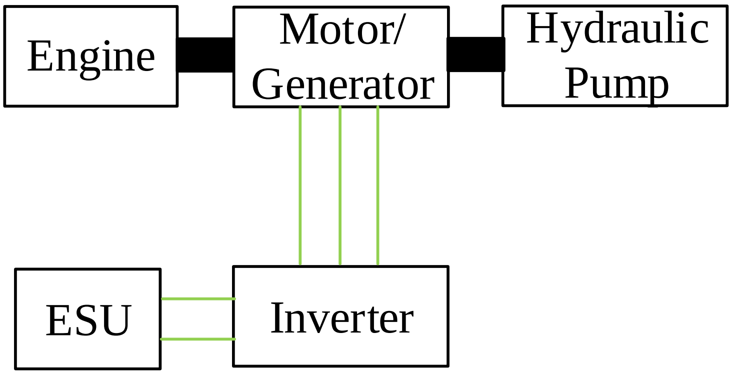

Fig. 2.12 *Structure of parallel hybrid system with motor/generator*

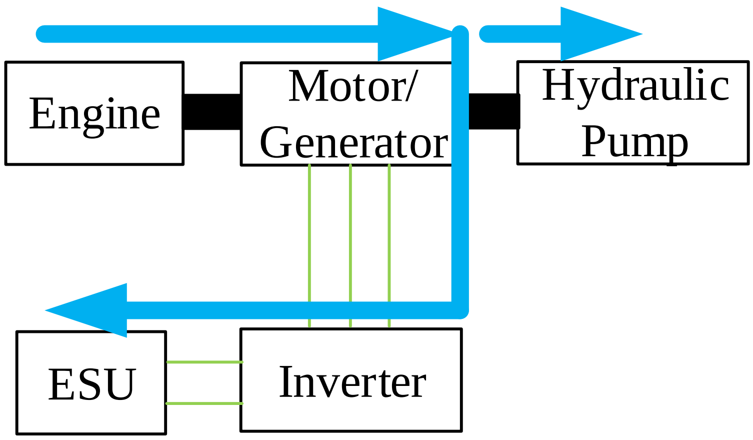

Fig. 2.13 *Energy flow of parallel hybrid system with motor/generator*

- Electric drive actuator:

The regenerated energy can also be used to drive the actuator directly, such as the electric swing system, shown in Fig.2.14. The stored energy in ESU can be used by the motor/generator to drive the upper structure of excavator swing system through a gear. This system can also regenerate energy during deceleration, in which the motor/generator works as a generator mode. The energy flow of energy reuse and energy regeneration are shown in Fig. 2.15 (a) and (b) respectively.

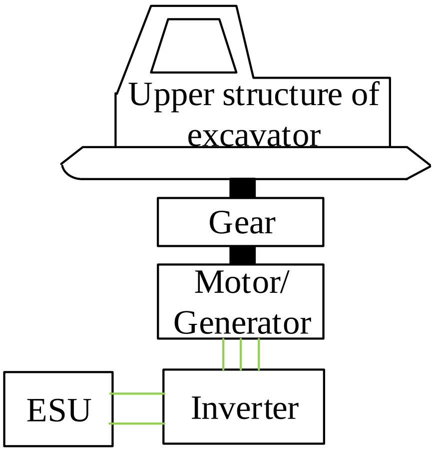

Fig. 2.14 *Structure of electric swing system*

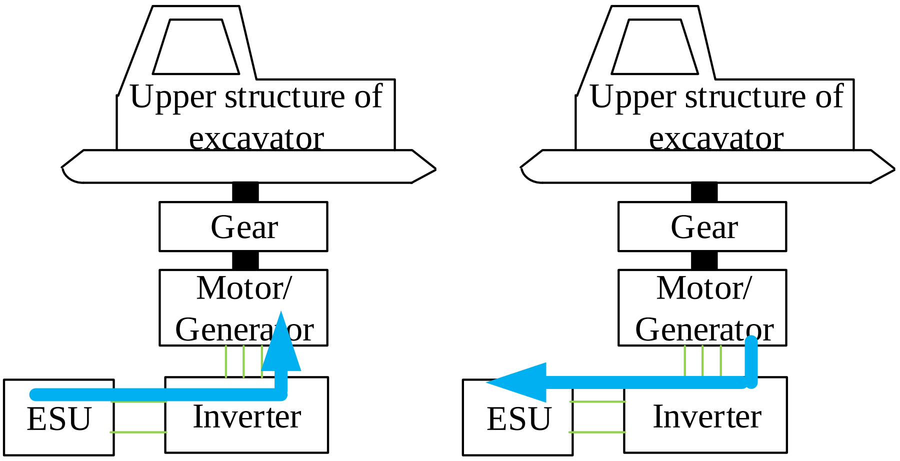

Fig. 2.15 *Energy flow of electric swing system*

The electric drive actuator needs much electric energy in operation. Hence, only energy regeneration system cannot provide enough energy to that. Hence, the electric drive actuator can be used in the series hybrid excavator and parallel hybrid excavator, shown in Fig. 2.16 and Fig. 2.17.

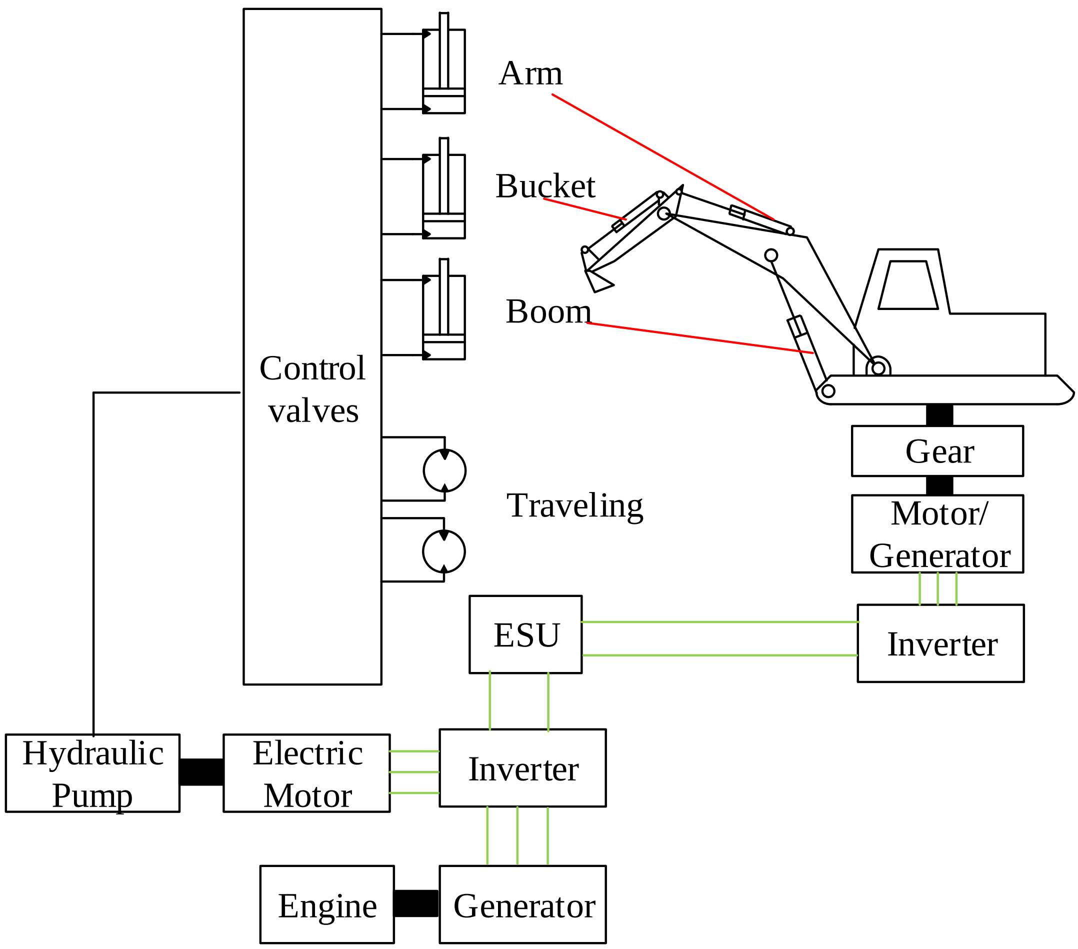

Fig. 2.16 *Electric swing system in series hybrid excavator*

In Fig. 2.16, the engine drives the generator to generate the electric energy to the electric motor and ESU. Hence, if the stored regenerated energy of ESU is not enough to drive the electric swing system, the engine will work to generate electric energy to ESU.

In Fig. 2.17, if the regenerated energy in ESU is not enough to drive electric swing system, the motor/generator will be worked as a generator to convert the energy from engine to electric energy to charge ESU.

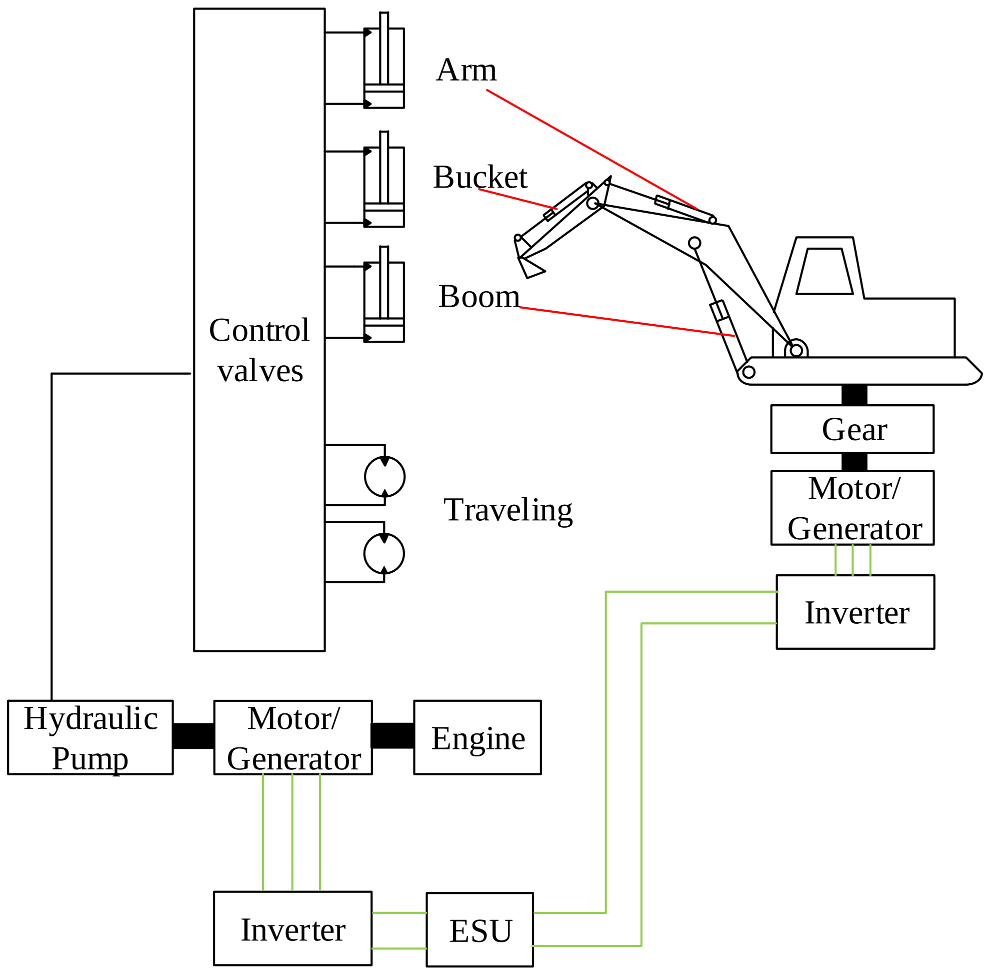

Fig. 2.17 *Electric swing system in parallel hybrid hydrualic excavator*

The electric drive actuator can also be used in the pure electric excavator, such as the electric swing system in electric hydraulic excavator in Fig. 2.18. The energy of ESU is charge by the grid mainly. The electric swing system can also regenerate the energy to charge the ESU. When, the swing system requires energy to accelerate, the ESU will provide the stored energy to the electric motor of swing system.

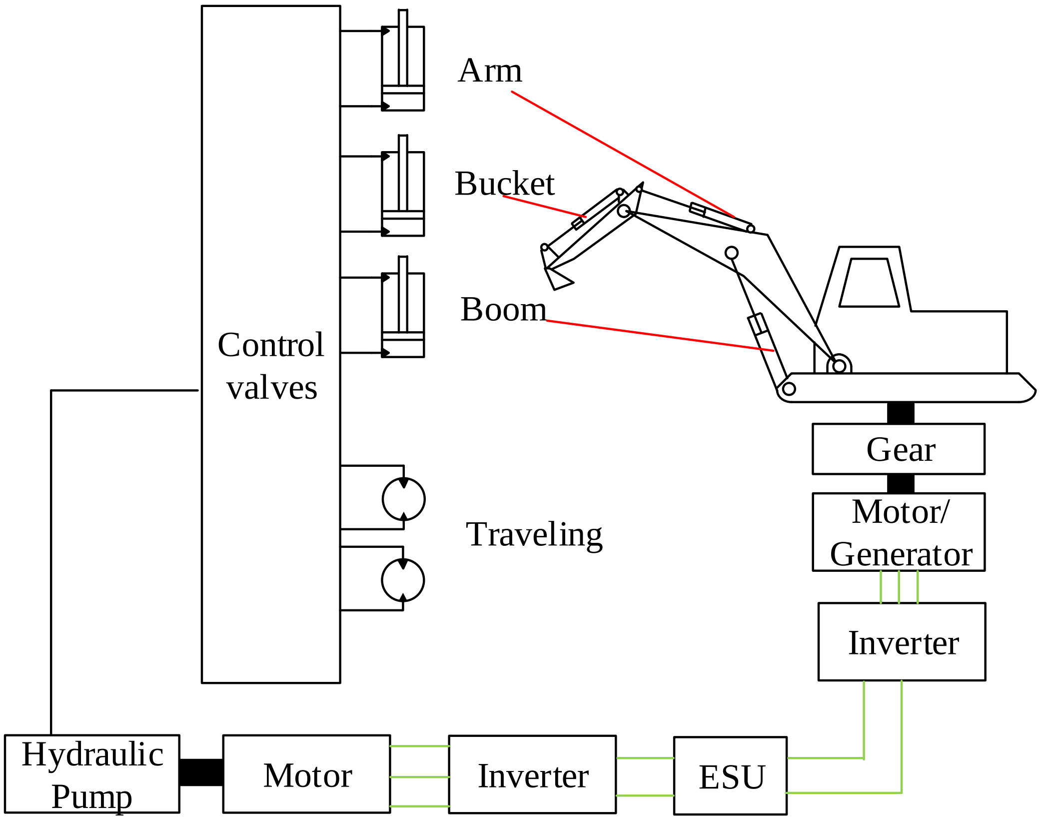

Fig. 2.18 *Electric swing system in pure electric hydrualic excavator*

2.2 Hydraulic hybrid excavator

The hydraulic hybrid excavator uses the hydraulic accumulator as the ESU, which is can be seen in Fig.2.19. The high-pressure source can charge the hydraulic accumulator, which can store the hydraulic energy. If the system needs energy form the hydraulic accumulator, the stored energy can be discharge. The three main types of hydraulic accumulators are weight-loaded, spring-loaded, and gas-charged, which are shown in Fig. 2.20.

Weight-loaded accumulators store the energy in the form of potential energy in the mass of the piston and load. It is charged by pumping the oil into the lower chamber, and then displacing the piston and load upward. The pressure variation due to piston displacement is of negligible value; therefore, this type delivers the oil at a constant pressure.

In the spring-type accumulator, the energy is stored as elastic energy of the spring. The spring is compressed by pumping oil into the accumulator. This class of accumulators delivers the oil at varying pressures. The delivery pressure of this type decreases with the spring relaxation due to the decrease of the spring force. The delivery pressure is proportional to the volume of oil in the oil chamber of the accumulator.

Weight-loaded and spring-type accumulators are not widely used, regardless of the simplicity of their construction and their possible fabrication using standard hydraulic cylinder barrels. This is due to their low response, large sizes, and working constraints. The most widely used accumulators are the gas-charged types, where the oil is stored under the pressure of a gas, usually nitrogen. The air can be used as a charging gas in the case of fire-resistant oils.

Fig. 2.19 *Hydrualic accumulator*

Gas-charged accumulators with separating elements consist of a steel body containing two chambers for the oil and the compressed nitrogen. The gas chamber is pre-charged with compressed nitrogen through a charging check valve. The charging process is carried out while the accumulator is completely empty of oil. The gas and oil chambers are completely separated. During operation, the oil is pumped into the oil chamber. When the oil pressure exceeds the gas-charging pressure, the oil flows into the accumulator, decreasing the gas volume and increasing its pressure. The steady-state equilibrium is reached when the oil pressure is equal to the gas pressure. The oil is stored at high pressure under the action of the compressed gas. This type of accumulator is widely used in hydraulic system, with high energy density and good performance.

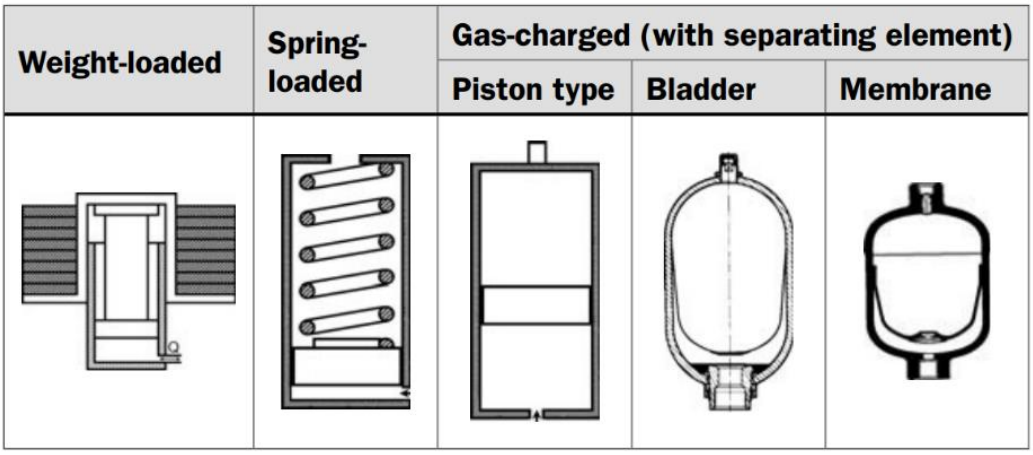

Fig. 2.20 *Basic types of hydraulic accumulator*

One application of hydraulic accumulator in swing system is shown in Fig.2.21. The hydraulic accumulator can be charged during deceleration of the swing part and provides flow during acceleration. Hence, the flow rate of hydraulic pump can be reduced. Then, the energy consumption is reduced.

The hydraulic accumulator is easy to set up in the hydraulic circuit with cheap price. But the energy regeneration efficiency and energy reuse efficiency are affected by the pressure of system and hydraulic accumulator. If the pressure of accumulator is higher than the system pressure, the hydraulic accumulator cannot regenerate more energy form the system. If the pressure of accumulator is lower than the system pressure, the accumulator cannot discharge the energy to the system. To solve this problem, the hydraulic transformer is designed and applied into the hydraulic hybrid excavator. A typical hydraulic transformer is shown in Fig. 2.22. Two pump and motor are connected. One of the pumps and motor is variable displacement component. If port b is connected to the hydraulic accumulator and the pressure of accumulator is higher than the system pressure (pressure of port a), the system can also charge the accumulator by controlling the displacement of the hydraulic transformer. Hence, more energy can be charged to the accumulator. If the accumulator pressure is lower than system pressure, the accumulator can also charge the system by controlling the displacement of hydraulic transformer.

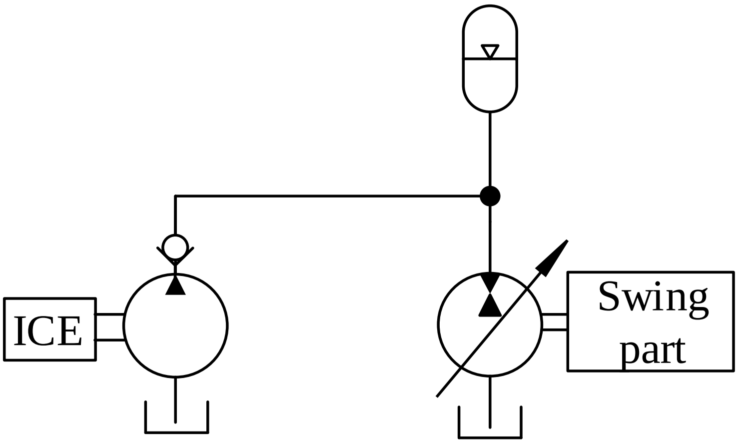

Fig. 2.21 *Swing system with hydrualic accumulator*

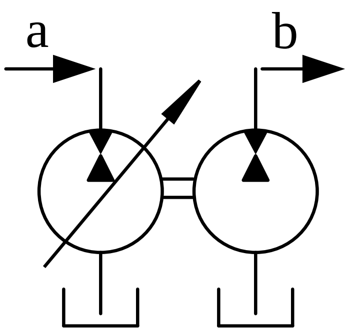

Fig. 2.22 *Hydraulic transformer*

The hydraulic transformer application on the excavator boom system is shown in Fig. 2.23[28]. The hydraulic accumulator is the ESU in the system. In boom down mode, the valve V_1 and V_2 are open, the hydraulic transformer works to regenerate the protentional energy of the load. The displacement of hydraulic motor is controlled to regulate the flow through the hydraulic transformer H_1. Then, the velocity of the boom cylinder can be controlled. If the hydraulic accumulator is charged fully, the valve V_3 will be controlled to regulate the flow rate of the boom cylinder. In this case, the valve V_1 and V_2 are closed.

In boom up mode, the valve V_1 and V_2 are open and the displacement of hydraulic motor is controlled to provide a stable flow rate to the boom cylinder. The flow rate from the hydraulic transformer is measured by flow rate sensor. The additional flow rate is provided by the main pump based on the required flow rate and the flow rate of hydraulic transformer. Hence, the pump and accumulator provide the flow rate together. In this process, the displacement of hydraulic transformer is controlled to reuse the stored energy of accumulator fully.

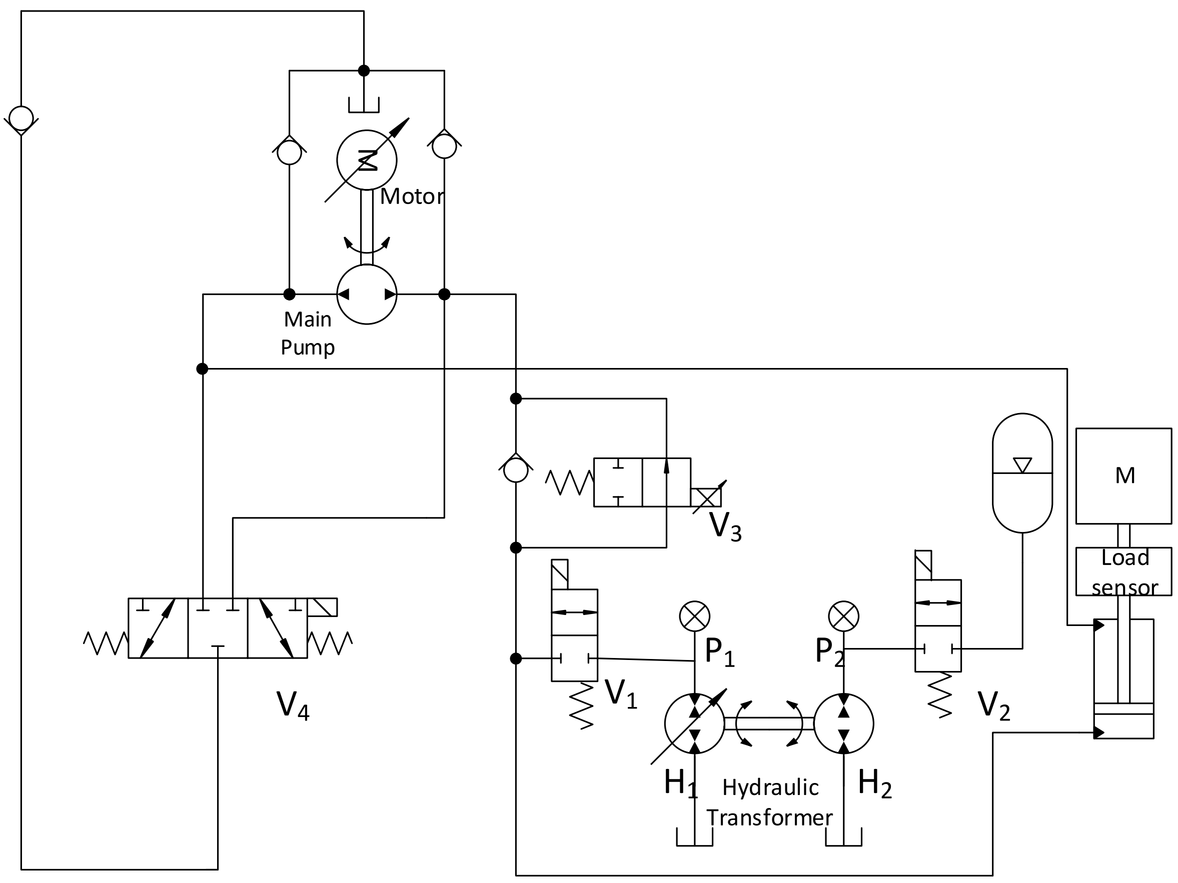

Fig. 2.23 *Boom system with hydraulic transformer[28]*

Another kind of hydraulic transformer has three port and can be utilized in the hydraulic hybrid excavator[41], [42]. The three-port hydraulic transformer is shown in Fig. 2.12. There are three ports on the valve plate in Fig. 2.24 (b). Port A is connected to the actuator. Port B is connected to the power source, such as hydraulic accumulator. Port T is connected to the tank. The valve plate can be rotated by controlling the handle in Fig. 2.24 (a). The flow rate of each port can be controlled by controlling the valve plate angle. If the pressure of hydraulic accumulator is lower than the pressure of actuator, the hydraulic transformer can increase the flow rate of hydraulic accumulator and reduce the flow rate of the actuator. Then hydraulic accumulator can discharge the energy to the actuator.

Fig. 2.24 *Three-port hydraulic transformer*

The hydraulic circuit of the CPR system with hydraulic transformer is shown in Fig. 2.25. The three-port hydraulic transformer working principle is same as the hydraulic transformer with two pump and motor. In this system, the three-port hydraulic transformer is connected to the head chamber of cylinder, high pressure rail and low-pressure rail. When the cylinder moves down, the protentional energy can be regenerated to store in the hydraulic accumulator through the hydraulic transformer. By controlling the valve plate angle of the hydraulic transformer, the hydraulic accumulator can be charged, even if the pressure of accumulator is higher than the pressure of the cylinder, and the lowing velocity of cylinder can also be controlled. When the cylinder moves up, the cylinder velocity and flow from the high-pressure rail can also be govern by controlling the valve plate angle of hydraulic transformer. However, the hydraulic transformer is expensive, and no commercial product can be bought. The controlling of the hydraulic transformer has much challenge in application.

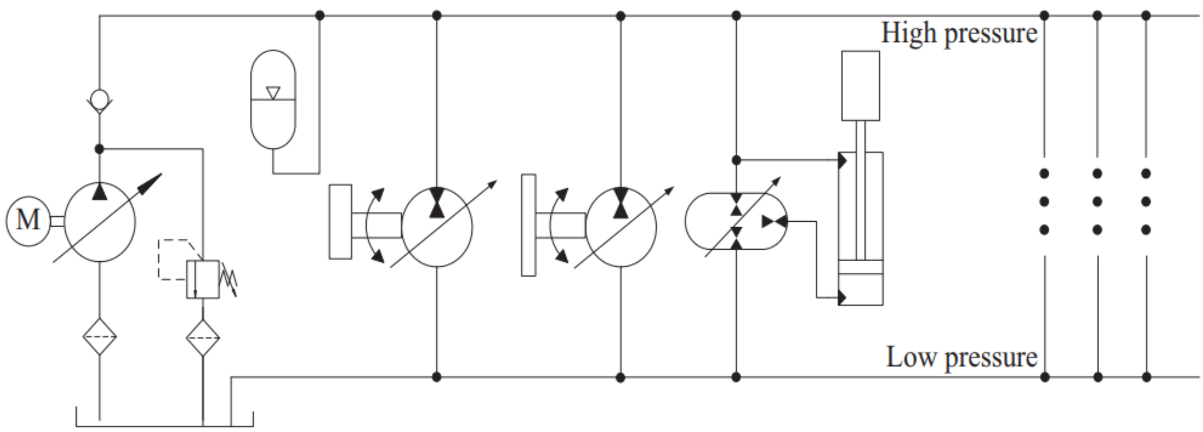

Fig. 2.25 *CPR system with hydrualic transformer*

2.3 Control technology of hybrid excavator

2.3.1 Energy regeneration part control

- Electric hybrid excavator:

The energy regeneration part not only regenerates the energy, but also affects the actuator's performance. Taking the boom system as an example, the generator speed affects the flow of the cylinder. Then the velocity of the cylinder is affected. In energy regeneration system with fixed displacement of hydraulic motor, the generator speed must be controlled to satisfy the velocity requirement of cylinder. Hence, two kind of control strategies are shown in Fig. 2.26 and Fig. 2.27 respectively.

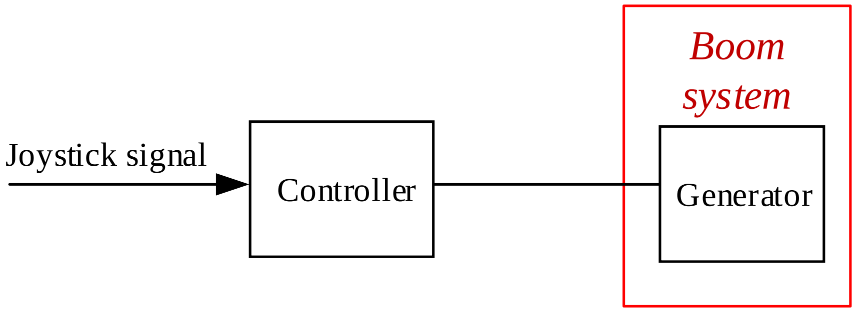

Fig. 2.26 *Control structure of electric energy regeneration system(1)*

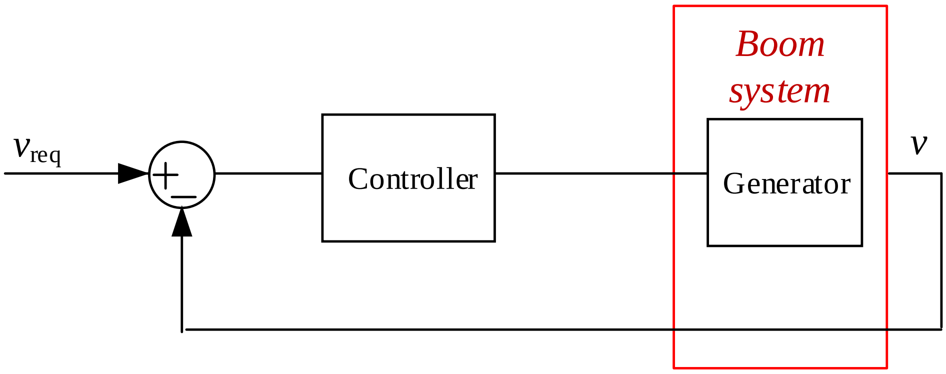

Fig. 2.27 *Control structure of electric energy regeneration system(2)*

In Fig. 2. 26, the joystick signal is the input signal of the controller. The output of controller is the control command of the generator to control the speed of the generator. Then the flow rate of the hydraulic motor and the cylinder is controlled. Finally, the velocity of the cylinder is regulated. This is an open loop control system. The closed loop control of the energy regeneration system in shown in Fig. 2.27. The required velocity V_{req} is calculated based on the joystick signal. The velocity of the cylinder is measured by sensor. The error between the required velocity and the measure velocity is the input signal of the controller. Then, the controller controls the generator speed. Compared with the open loop control method, this method could control the velocity of cylinder with a higher accuracy. But setting a sensor on the boom cylinder has challenges, because the boom cylinder works in severe environment of real excavator. The stability of the sensor should be considered. In the fixed HMD system, the generator must be controlled based on the velocity requirement. The energy regeneration efficiency cannot be optimized. The generator working points cannot always located in the high efficiency range.

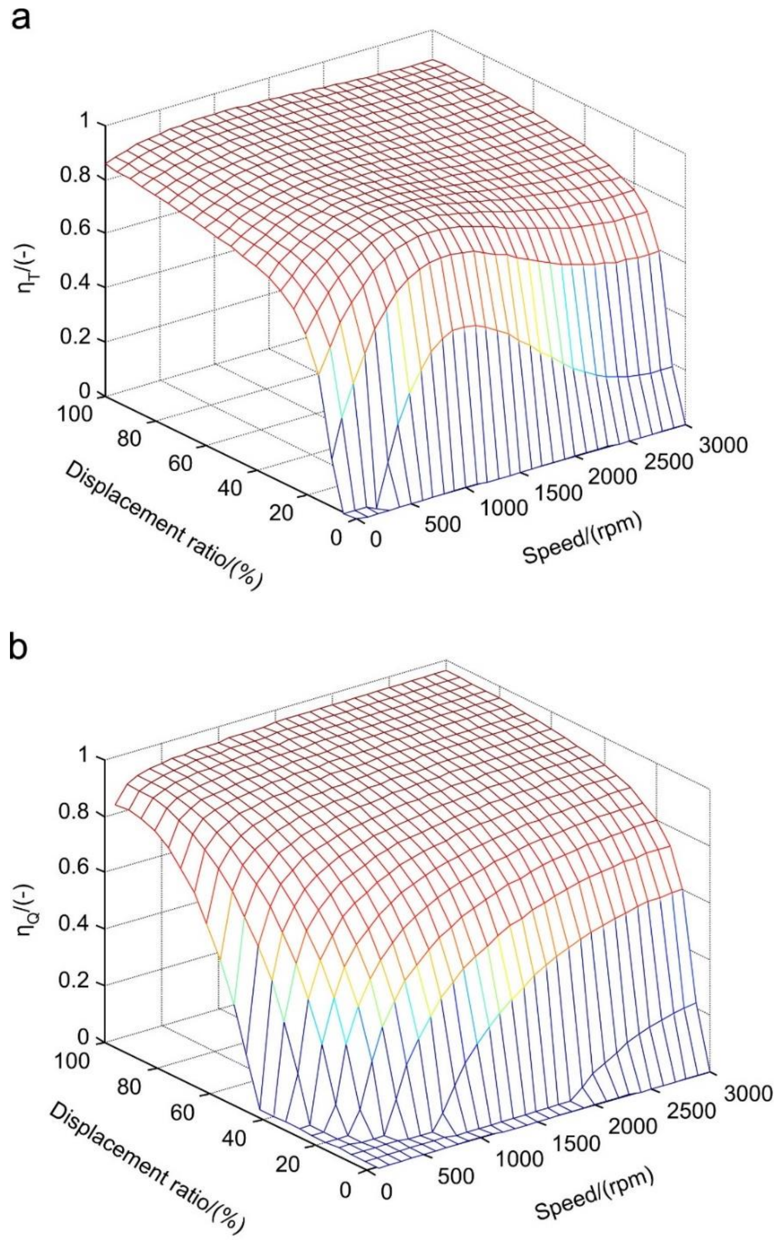

Fig. 2.28 *Efficiency map of hydrualic motor(a.torque efficiency, and b. volumetric efficiency)*

In the variable displacement hydraulic motor system, both generator speed and HMD can be controlled. If the HMD is decreased and the generator speed is increased accordingly, the flow rate of hydraulic motor can be kept constant. So, there are infinite combination of generator speed and HMD in a specific flow rate of hydraulic motor. But the efficiency of the generator is varied based on different speed and torque. The efficiency of hydraulic motor is also varied based on different pressure, flow rate and HMD. One example of efficiency map of hydraulic accumulator is shown in Fig.2.28[17]. One efficiency map of generator is shown in Fig. 2.29[43].

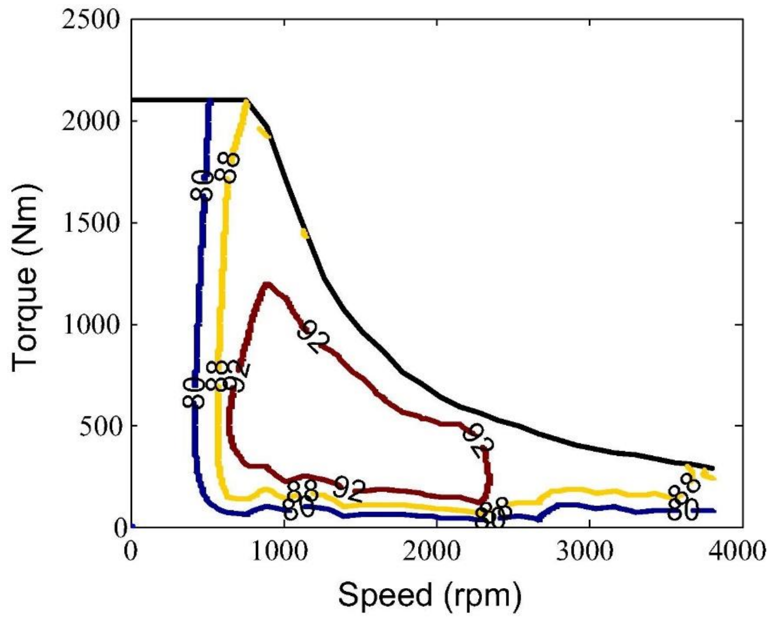

Fig. 2.29 *Efficiency map of generator*

The torque efficiency and volumetric efficiency of hydraulic motor are shown in Fig. 2.28 (a) and (b) respectively. Normally, the total efficiency of the hydraulic motor is high with large HMD and speed. The tendency can be seen in Fig. 2.28. The high efficiency range of generator is in area of middle speed and low torque in Fig. 2.29. The high efficiency area is different of different kinds of generator. Normally, the high efficiency range of generator cannot always match the high efficiency rang of hydraulic motor. When the HMD and generator speed are changed, both working efficiency of generator and hydraulic motor are changed.

Hence, the optimal displacement of the hydraulic motor and generator speed can be calculated based on the efficiency map of generator and hydraulic motor. One control strategy is shown in Fig. 2.30[44]. In Fig. 2.30, the pressure of the head chamber of cylinder P_c is measured and the required flow rate q_{req} is calculated based on the joystick signal. These two parameters are used to calculate the efficiency in each condition of HMD and generator speed by using the efficiency map of hydraulic motor and generator. Then, the optimal HMD and generator speed can be got among all the candidate combination of HMD and generator speed. The calculation of the optimal HMD is shown in Fig. 2.31. The mechanical efficiency map, volumetric efficiency map and generator efficiency map are used to calculate the total efficiency in HMD. Then, the optimal HMD is selected with highest total efficiency.

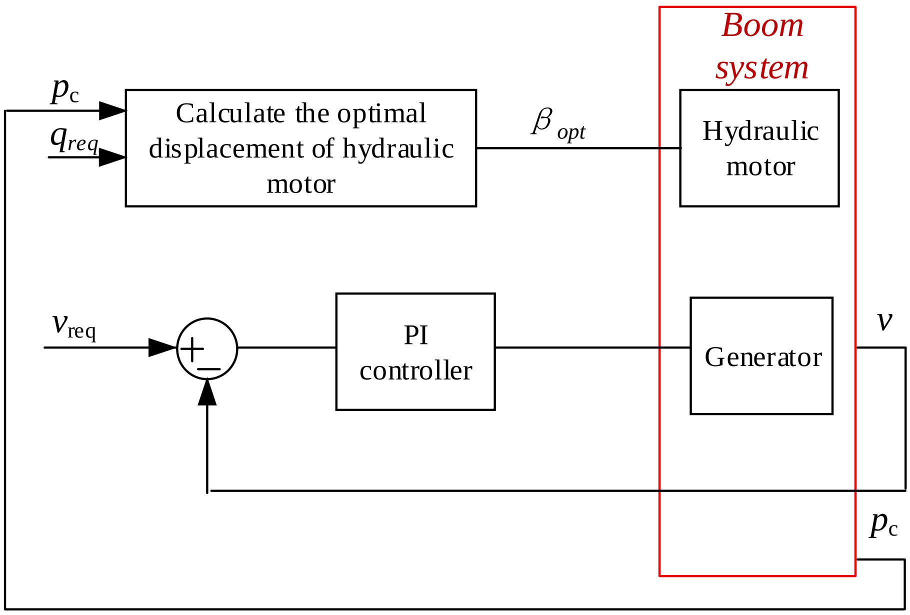

Fig. 2.30 *Control strategy of variable HMD system[44]*

Next, the calculated optimal HMD is sued to control the hydraulic motor. The calculated optimal speed of generator can also be used to control the generator. But, in Fig.2.30, the speed of generator is controlled by a PI controller based on the error of the required velocity v_{req} and measured velocity v, because the system performance is also considered in this control strategy. In this method, the cylinder velocity can follow the joystick signal with high accuracy. Both energy regeneration and system performance are considered in this control strategy.

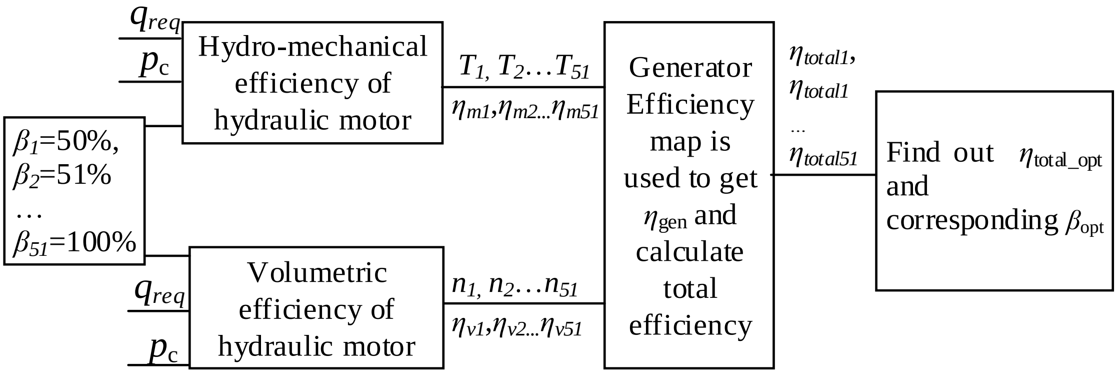

Fig. 2.31 *Calculation of optimal HMD*

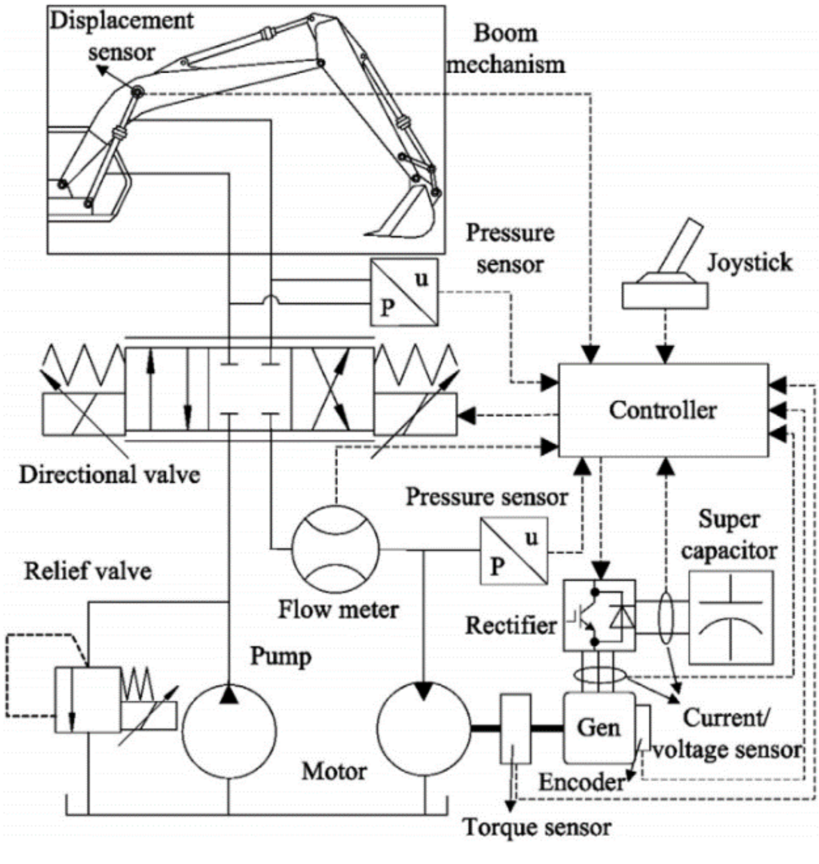

Fig. 2.32 *Structure of the energy regeneration system with valve control*

The combination of valve control and generator speed control are applied in the energy regeneration system to improve the performance of the system. The structure of the system is shown in Fig. 2.32. At the beginning of boom down, the direction valve controls the flow of the cylinder. Then the generator starts to work and governs the flow of the cylinder. Compared with the only generator speed control system, the fluctuation of the boom cylinder is reduced at the beginning of boom down. In boom down mode, the displacement of cylinder is measured as a feedback signal of the controller to control the directional valve and generator speed.

Based on above discussion, the energy regeneration efficiency and system performance are the main points to be considered in control strategy design. The HMD, generator speed and valves are controlled to realize high energy regeneration efficiency and good performance.

- Hydraulic hybrid excavator:

To reduce the affection of the hydraulic accumulator pressure and improve the energy regeneration efficiency, the HMD control, valve control and hydraulic transformer control were utilized in the energy regeneration system. During energy regeneration, the pressure of the accumulator is increased. The increased pressure may affect the performance of the actuator. Such as the swing system in Fig. 2.21, the variable hydraulic motor is controlled to avoid the required flow to be affected. If the pressure of the accumulator is increased, the flow rate from the hydraulic motor to the accumulator will be decreased without control of HMD. Then the speed of the swing part is decreased. Normally, this deceleration cannot match the joystick signal. Hence, the HMD should be adjusted to ensure the speed of swing part follows the joystick signal. A typical control diagram is shown in Fig. 2.33.

In Fig.2.33, the reference speed is calculated form the joystick signal. The error of the reference speed and measured swing speed is used as the input of the controller. Then the controller controls the HMD to ensure the system performance.

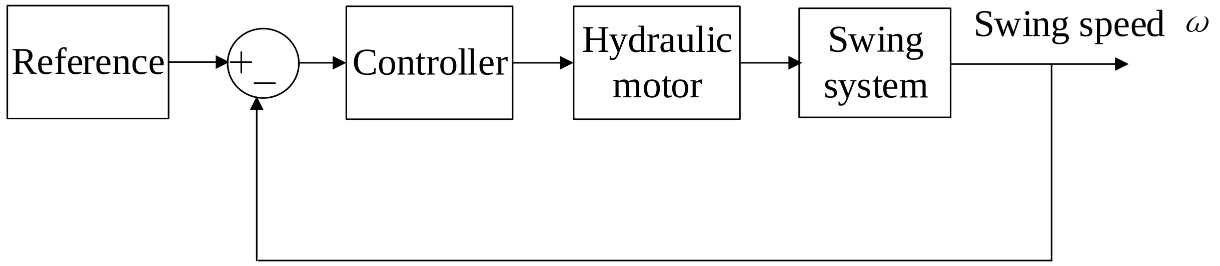

Fig. 2.33 *Control straegy of HMD of swing system*

In the hydraulic transformer system, such as the boom system in Fig. 2.34, the displacement of hydraulic transformer should be controlled to regulate the flow rate of the boom cylinder. The control diagram is shown in Fig. 2.35.

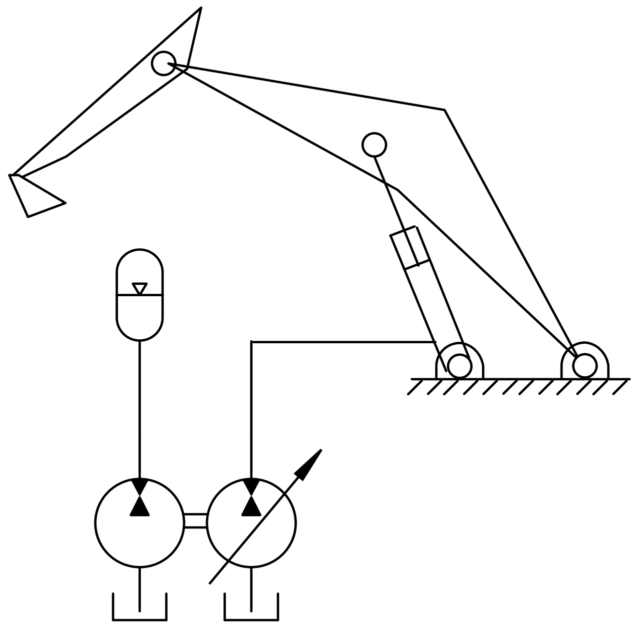

Fig. 2.34 *Enrgy regeneration boom system with hysrualic transformer*

In Fig.2.35, the velocity of the boom cylinder is measured, and the error of reference velocity and measure velocity of boom cylinder is the input signal of hydraulic transformer. In energy regeneration process, the pressure of the accumulator increases continually to store the regenerated energy. The increased pressure leads to speed decrease of hydraulic transformer, without control of the displacement of hydraulic transformer. Then the flow rate and velocity of the cylinder are decreased, in which the velocity of the cylinder cannot match the joystick signal. If the cylinder needs a constant velocity to move down with increasing of accumulator pressure, the displacement of hydraulic transformer should be decreased accordingly to keep the flow from the cylinder constant. Hence, the control of the hydraulic transformer is important to ensure the system performance.

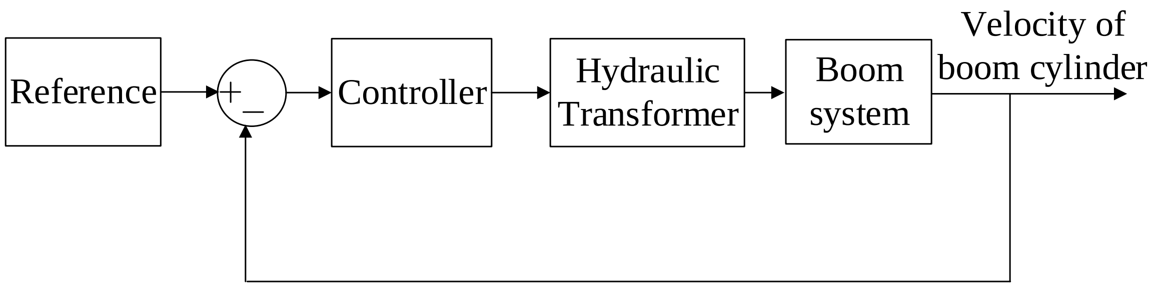

Fig. 2.35 *Control diagram of the boom system with hysrualic transformer*

2.3.2 Energy reuse part control

In energy saving of hybrid excavator, most of the research focused on the energy regeneration and there are few researches about the energy reuse. Normally, only structure of the energy reuse was proposed in the publication. There are few researched discussed the control strategy of energy reuse.

- Electric hybrid excavator:

The series hybrid system and parallel hybrid system were discussed in the above section. In series hybrid system, the engine is decoupled from the load, and only drives the generator to provide electric energy. The key point of the system control is the energy distribution of engine and ESU.

The engine can work with a constant speed and torque, which is a high efficiency working point. So, the engine output energy is a constant value. But the power requirement of system is a variable, which is decided by the load and joystick signal. The power requirement is always different from the engine output power. Then differences power is provided by the ESU. With this control strategy, the engine can always work in high efficiency point, and the system power requirement also can be satisfied. The control diagram is shown in Fig. 2.36

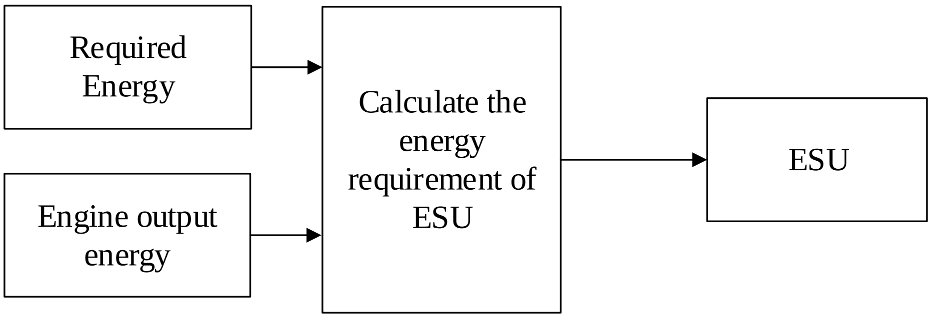

Fig. 2.36 *Control diagram of serise hybrid system (1)*

In some cases, the SOC of ESU also needs to be considered as a reference parameter to adjust the engine working points. Because the SOC of ESU should be controlled at a suitable range to ensure enough energy storage for emergency high energy requirement and to keep the ESU works at a high efficiency. Hence, the engine working points can be adjusted in a high efficiency range to keep the SOC of ESU in an expected range. The control strategy diagram is shown in Fig. 2.37.

In parallel hybrid system, the engine and the motor/generator are connected coaxially. The key point of the control strategy is the energy distribution of engine and the motor/generator, in which the main principle is same as the control strategy of the series hybrid system. But the parallel system distributes the energy through the torque control. The engine and the motor/generator are always running with the same speed, which is decided by the required flow rate of the pump. The required torque can be divided by engine and motor/generator. The engine can always work at a constant torque with a high efficiency. Then motor/generator provide the remnant torque. The engine can also adjust the torque output based on the engine efficiency map and SOC of ESU, in which the principle is same as that of the series hybrid system. The control diagram is shown in Fig. 2.38.

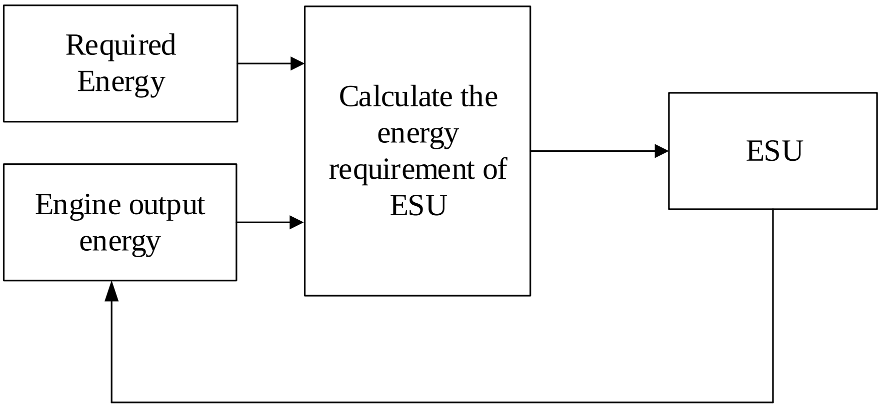

Fig. 2.37 *Control diagram of series hybrid system (2)*

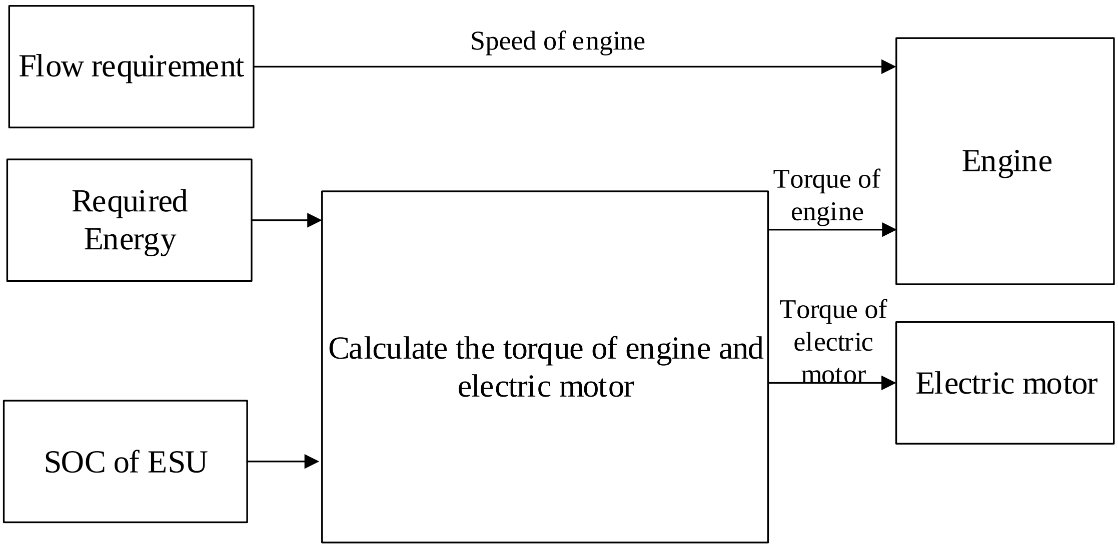

Fig. 2.38 *Control diagram of parallel hybrid system*

- Hydraulic hybrid excavator:

In energy reuse mode, the sorted energy in hydraulic accumulator can be reused to provide flow rate to reduce the flow rate from the hydraulic pump. The key point is flow distribution of hydraulic accumulator and hydraulic pump. The control diagram is shown in Fig.2.39. The required flow is calculated by the joystick signal. The control strategy divides the required flow rate to two parts. In energy reuse process, the hydraulic accumulator pressure decreases. Hence, the flow rate of hydraulic accumulator is difficult to be controlled. Normally, the control valve is used to regulate the flow from the hydraulic accumulator. Hence, the flow rate of hydraulic accumulator is controlled by valves. The throttling loose of the valve is an important factor, which is needed to be considered in the control strategy design.

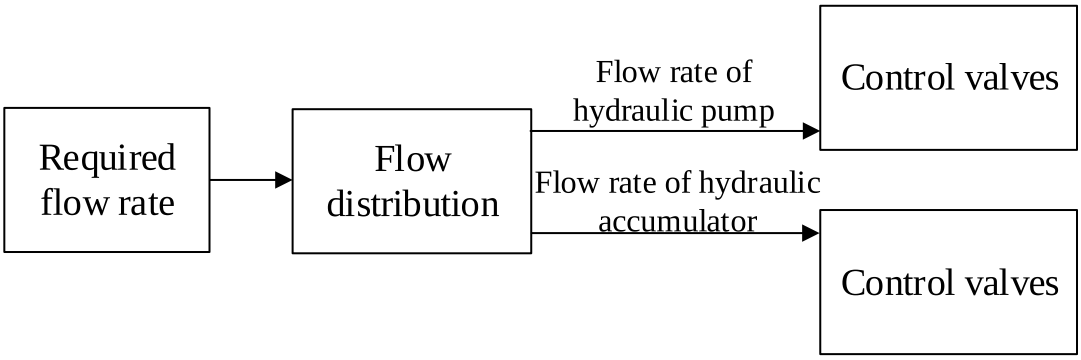

Fig. 2.39 *Control diagram of hydrualic hybrid energy reuse*

To avoid the throttling loose, the hydraulic transformer is used in hydraulic hybrid system. When the system reuses the energy from the hydraulic accumulator, the hydraulic transformer works to regulate the flow rate from the hydraulic accumulator. The control diagram is shown in Fig. 2.39. The flow distribution model distributes required flow rate of hydraulic pump and flow rate of hydraulic accumulator. The displacement of hydraulic motor is controlled to satisfy the required flow rate of the hydraulic accumulator. If the pressure of the hydraulic accumulator is lower than the system pressure, the hydraulic accumulator can also provide the energy to system. Because, the hydraulic transformer can realize that the low-pressure source provides flow to the high-pressure actuator. Hence, more energy can be reused by using hydraulic transformer. In this system, more flow rate requirement can be asked from the hydraulic accumulator in the flow distribution control strategy design.

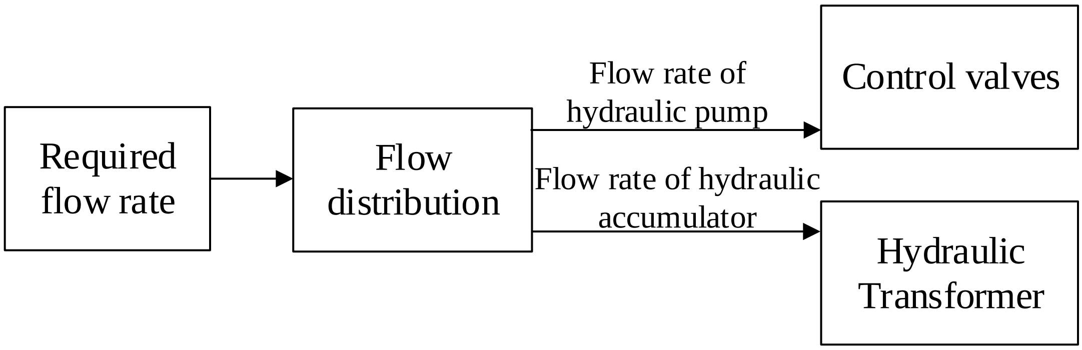

Fig. 2.40 *Control diagram of hydrualic hybrid energy reuse with hydraulic transformer*

In control strategy design of energy reuse, the final pressure of hydraulic accumulator also needs to be considered. If the hydraulic accumulator pressure is very low at the end of energy reuse process, the control valves or hydraulic transformer will be controlled to limit the flow rate of the hydraulic accumulator in energy regeneration mode of next cycle. Because, the large pressure difference between system and hydraulic accumulator may leads to large flow rate, and actuator may out of control without limitation of the flow rate. But the energy regeneration efficiency is affected with limitation of the flow rate. If the pressure of accumulator is very high at the end of energy reuse process, the energy will be difficult to be regenerated. The hydraulic transformer could solve this problem. But the working range of hydraulic transformer is limited. So, both much high pressure and much low pressure of accumulator may lead to low energy saving efficiency. In the control strategy design, the pressure of hydraulic accumulator should be considered.

- Electric drive actuator:

The utilization of electric drive actuator of excavator is swing system mostly. The electric motor could drive the upper structure of the excavator through the gear. Hence, the speed of electric motor is controlled based on the joystick command to ensure the system performance requirement.

The electric swing system is used in the pure electric excavator or electric hybrid excavator, because only energy regeneration system cannot regenerate enough energy to drive an electric swing system. In the electric hybrid system, the SOC of battery needs to be considered. The electric swing system costs much energy during acceleration. Hence, the SOC of the battery should be kept at a high level for operation of swing system. The engine also can drive the generator to generate the energy to run the electric swing system. In this process, the engine working points and energy conversion efficiency are very important to be considered. The engine and the ESU can provide the energy together to the electric swing system, which is shown in Fig.2.41. Hence, the energy management control is very complex, and the energy consumption needs to be optimized in control strategy design.

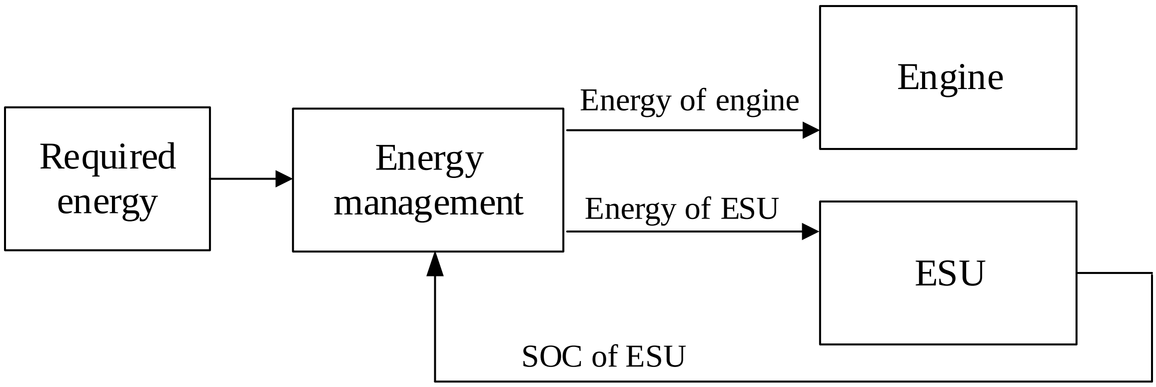

Fig. 2.41 *Control diagram of energy managemenrt*

Chapter 3. STRUCTURE OF THE PROPOSED SYSTEM

In exist research of energy saving of hydraulic excavator, most of the researches are energy regeneration of boom system. There are few researches about the energy reuse and energy saving of swing system of excavator. However, the swing system of the excavator has the protentional to regenerate the kinetic energy during deceleration of upper structure. 19% of energy consumption of excavator comes from the swing system. Hence, in this paper, the energy saving of swing system is researched, in which both energy regeneration and energy reuse are researched.

3.1 Proposed system design

The hybrid technology is chosen to be used in the proposed system. The electric hybrid technology could regenerate the energy easily by using the generator. However, the cost of the electric hybrid system is so high, because there are many electric additional components, such as electric motor, generator, inverter and battery or supercapacitor. It is hard to be realized in the commercial product. Hence, the hydraulic hybrid technology is chosen to be used in the swing system with easy installation and low cost. Hydraulic hybrid system with hydraulic transformer has good performance and energy saving efficiency. However, there is not commercial hydraulic transformer. Hence, the application of hydraulic transformer in engineering is difficult with high cost. Based on the above analysis, the swing system with hydraulic accumulator, variable displacement hydraulic motor and FCV is proposed in this paper. The hydraulic circuit of the proposed system is shown in Fig. 3.1.

Two independent hydraulic accumulators are used in the system to store regenerated energy. A variable hydraulic motor is used in the system to improve the performance of the system. An FCV is installed to govern the flow rate through the hydraulic accumulator in energy regeneration mode. Both variable hydraulic motor and FCV can control the flow rate of hydraulic accumulator and affect the performance of the system. The working principles in deceleration mode and acceleration mode are shown below.

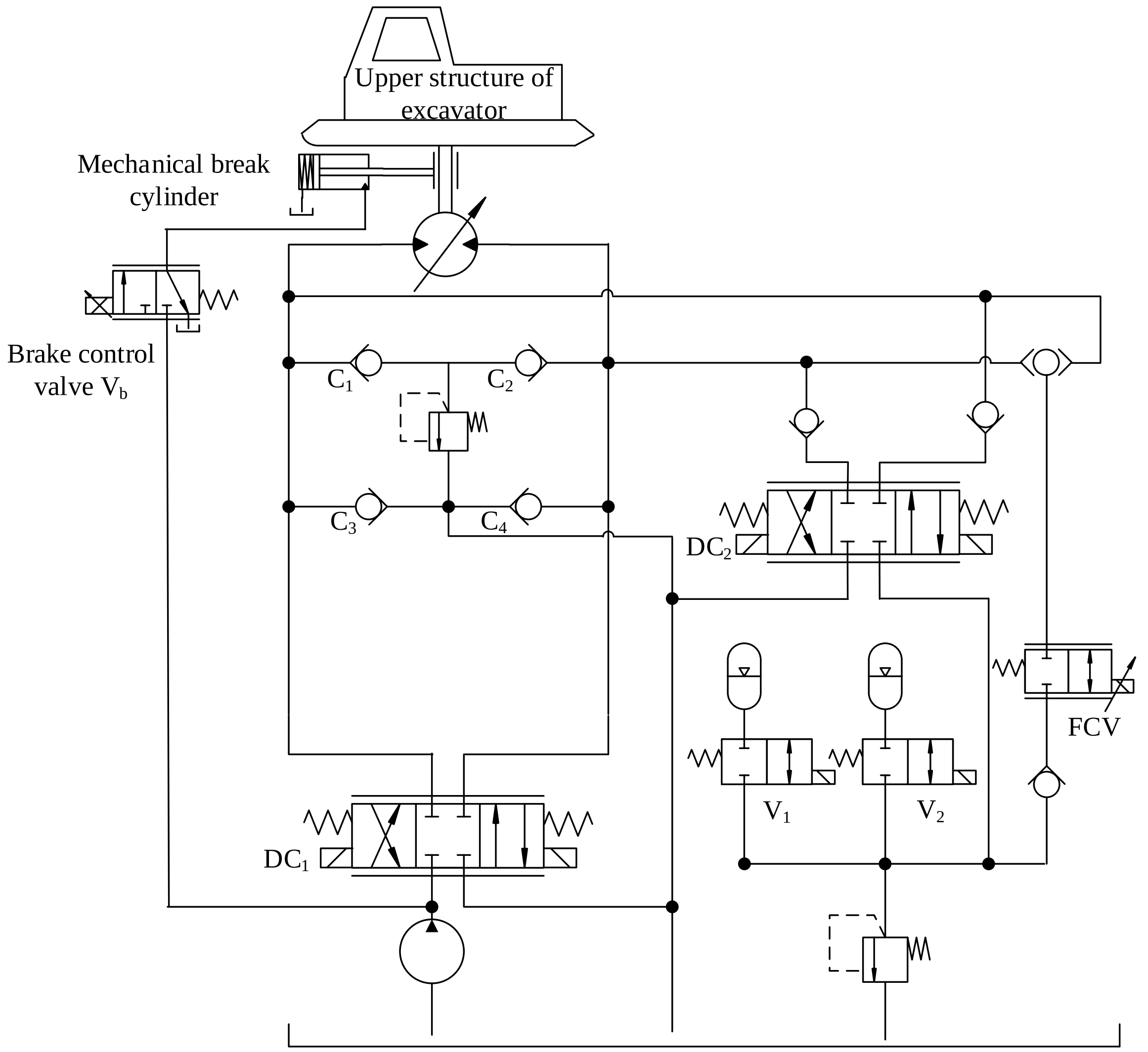

Fig. 3.1 *Proposed swing system*

When the upper structure decelerates, the system works in energy regeneration mode. The directional control valves DC_1 and DC_2 work in middle position and the flow control valve (FCV) controls the flow rate through the accumulator. The variable-displacement hydraulic motor controls the speed of the swing part and pulls fluid from the tank through check valve C_3 and C_4 during deceleration. When the swing part approaches to stop, the mechanical break stops the swing part. To improve the energy regeneration efficiency, the number of working accumulators can be controlled, in which one accumulator or two accumulators can be chosen to work, based on the control strategy. The flow direction of the system is shown in Fig.3.2. The high-pressure rails and low-pressure reals are shown with red color and blue color respectively.

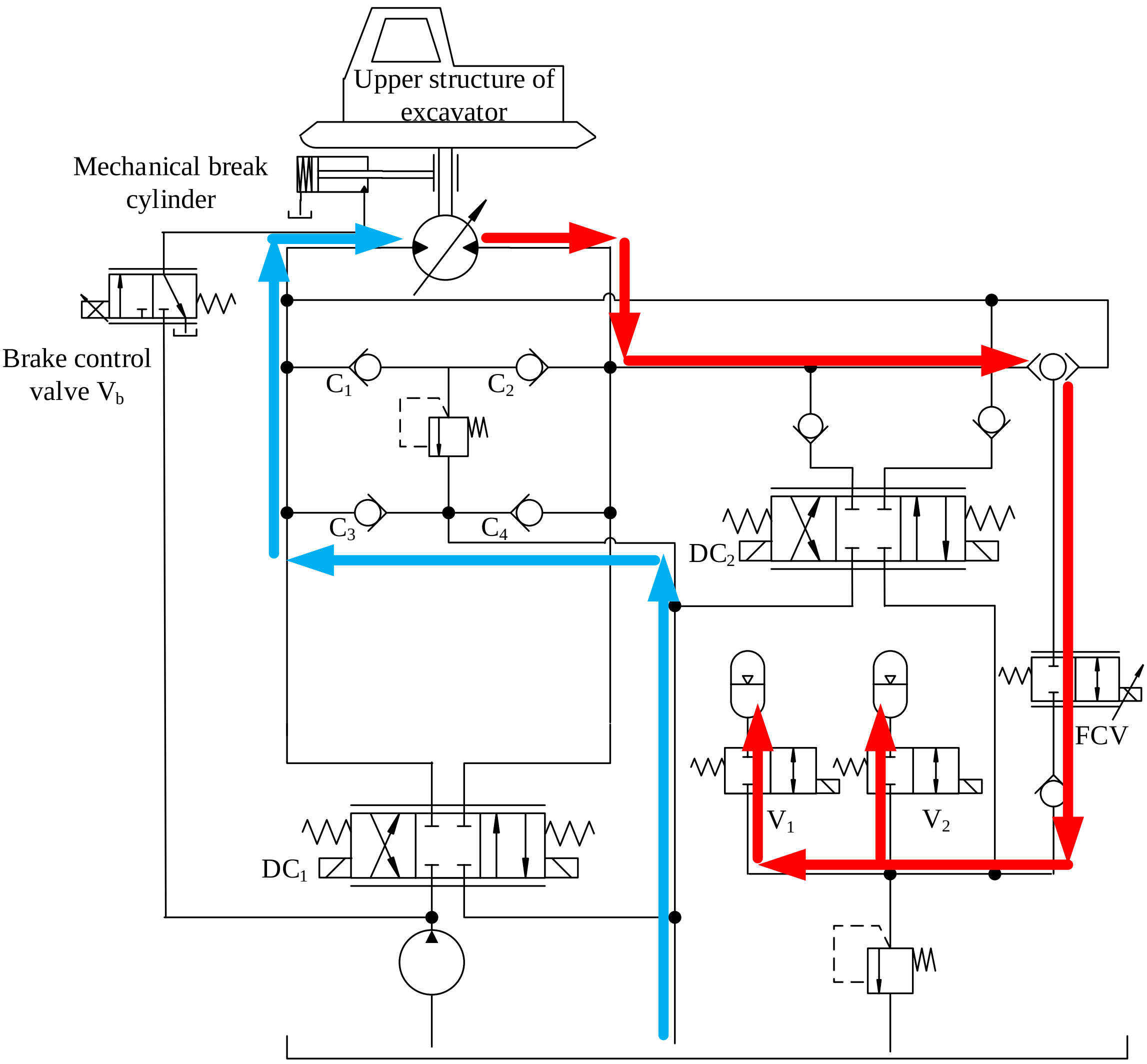

Fig. 3.2 *Flow direction of deceleration mode*

When the swing part accelerates, the system can work in energy reuse mode. The valve DC_1 works in left or right position to control the rotational direction of swing part, and DC_2 works to control the flow rate of hydraulic accumulator to assist the main pump. The flow direction of this mode is shown in Fig. 3.3.

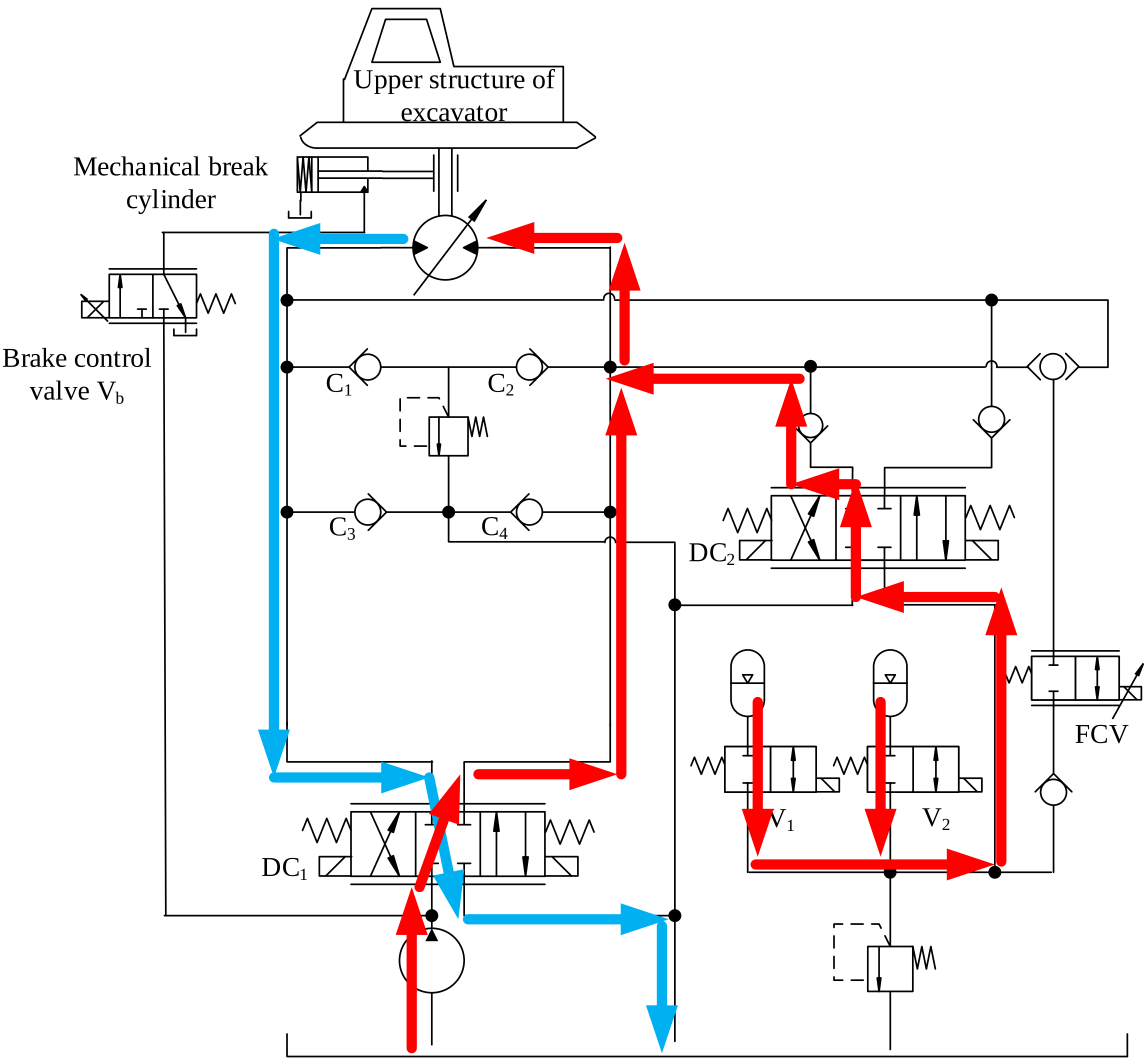

Fig. 3.3 *Flow direction of energy reuse mode 1*

The valve DC_1 can also closed, and DC_2 controls the flow from accumulator to the hydraulic motor. In this case, the hydraulic pump can be stopped and only the hydraulic accumulator provides energy to run the system. Hence, the stored energy can be reused in energy regeneration mode. The flow direction is shown in Fig. 3.4. If the hydraulic accumulator cannot provide the energy during acceleration, the total energy can be provided by the pump. The flow direction is shown in Fig. 3.5.

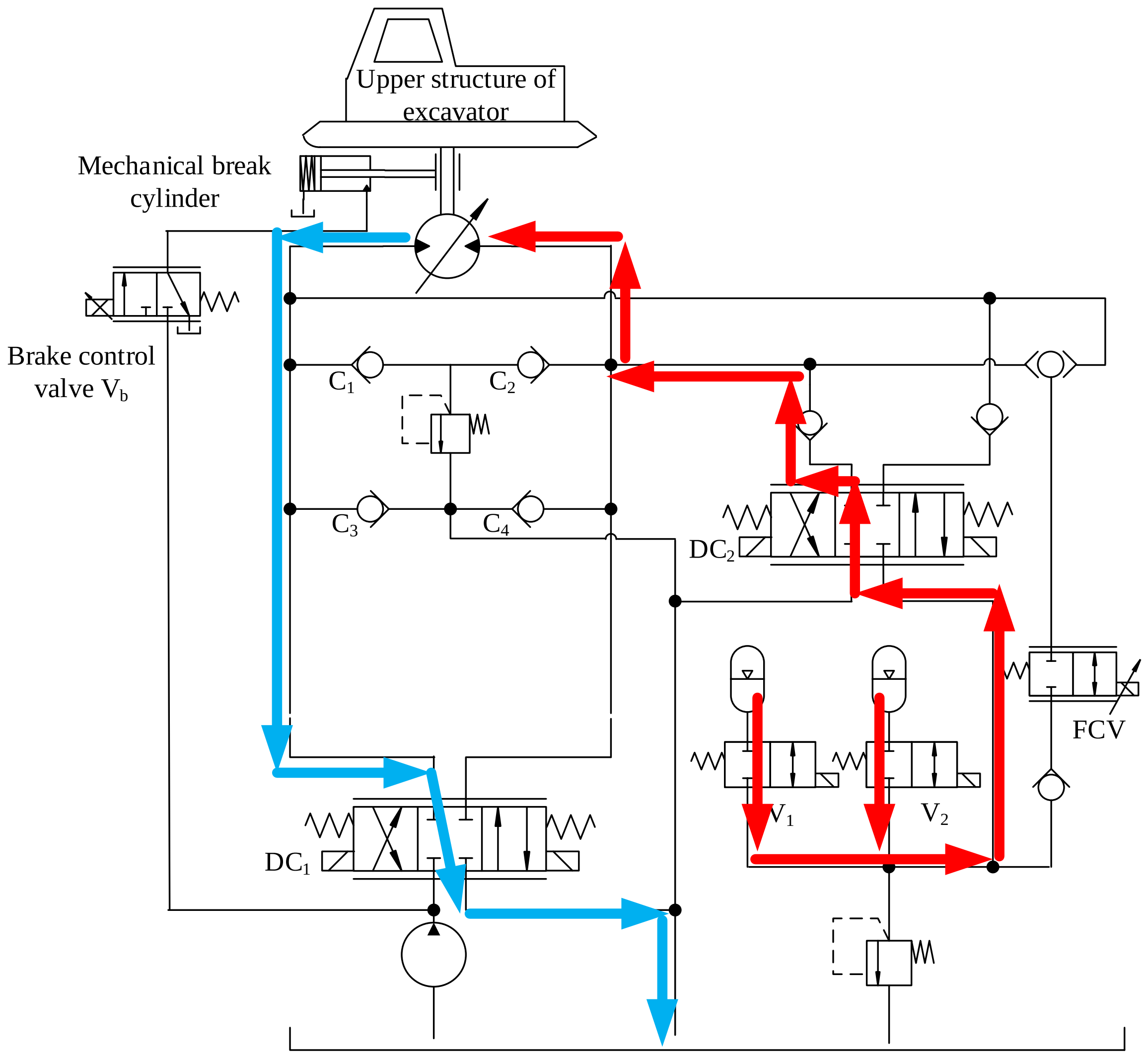

Fig. 3.4 *Flow direction of energy reuse mode 2*

There are three working modes can be selected during acceleration. The working modes are concluded and shown below:

1. Only main pump provides energy.
2. Only hydraulic accumulator provides energy.
3. Both main pump and hydraulic accumulator provides energy.

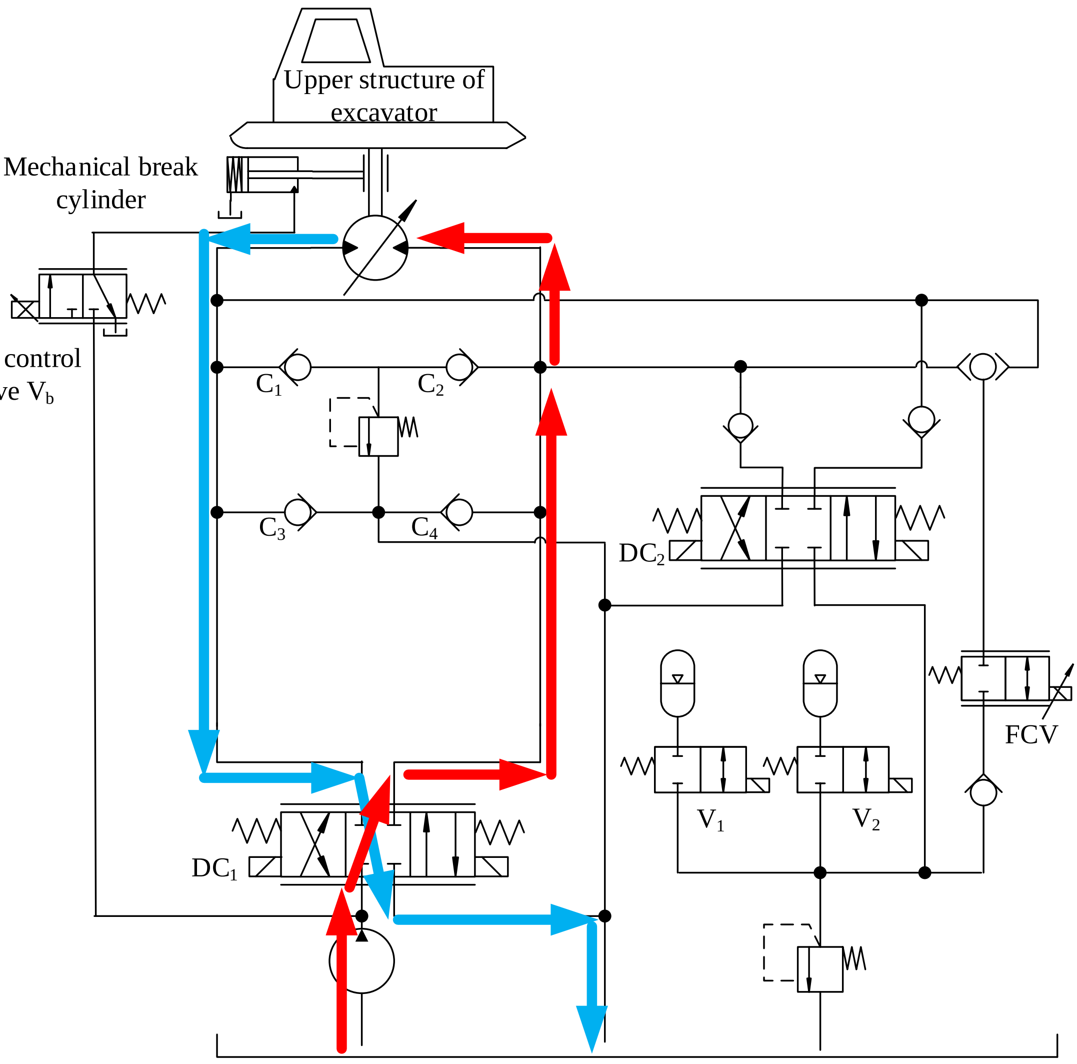

Fig. 3.5 *Flow direction of conventional acceleration mode*

Compared with the conventional system, the proposed system uses hydraulic accumulator and several hydraulic components additionally. These additional components are commercial hydraulic products and easy to be set up in the hydraulic system with low cost. In the system design, not only energy saving but also the system performance is considered. Hence, this system is easy to be utilized in the real hydraulic excavator with good performance and low cost.

3.2 Test bench design

The testbench is built in lab, which is shown in Fig. 3.6 and Fig. 3.7 and hydraulic circuit is shown in Fig. 3.8. Two pieces of flywheels are set in test bench instead of the upper structure of the excavator. Two pieces of flywheels (Fig.3.7) can be connected to the hydraulic motor coaxially to realize highest inertia. To test energy regeneration efficiency with different inertia, flywheel 1 can be removed to realize low inertia. Two independent hydraulic accumulators are shown in Fig. 3.7. The manual hydraulic valves V_1 and V_2 are set up in testbench to control the number of working accumulators. The components of the test bench are shown in table 3.1, and the key parameters of the test bench is shown in table 3.2.

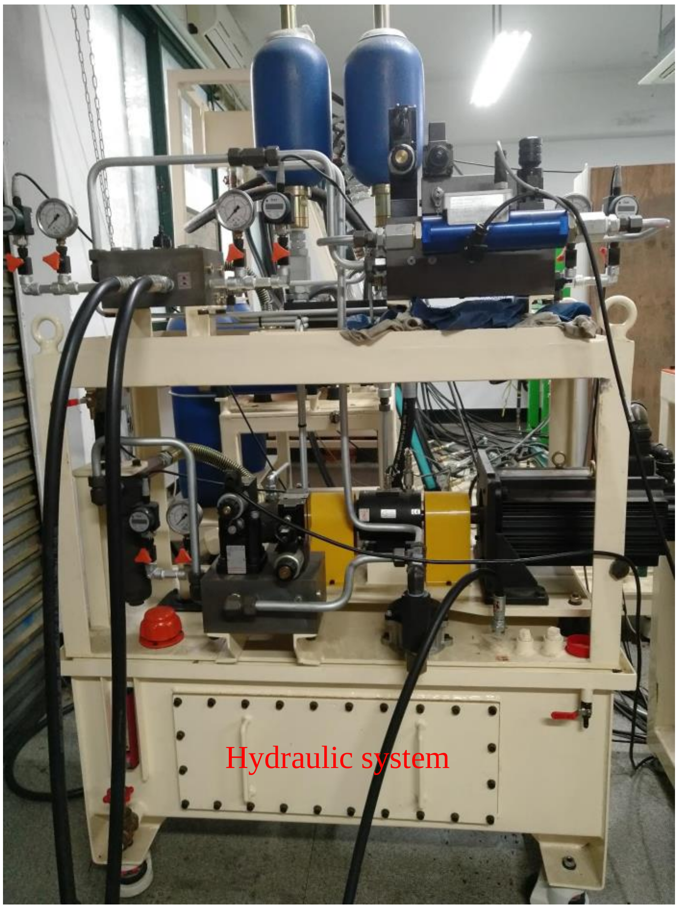

Fig. 3.6 *Hydrualic system of the test bnech*

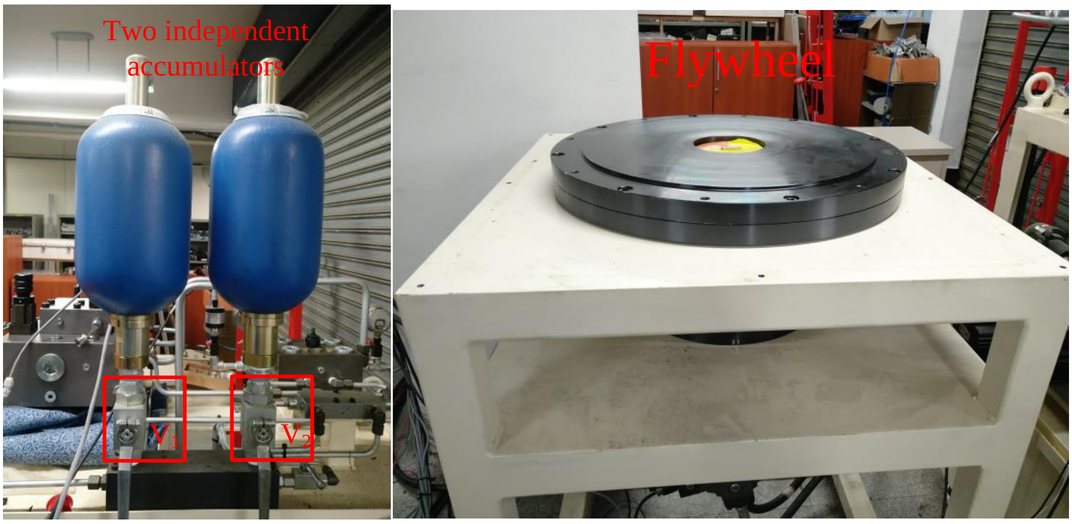

Fig. 3.7 *Hydrualic accumulator and flywheel in test bench*

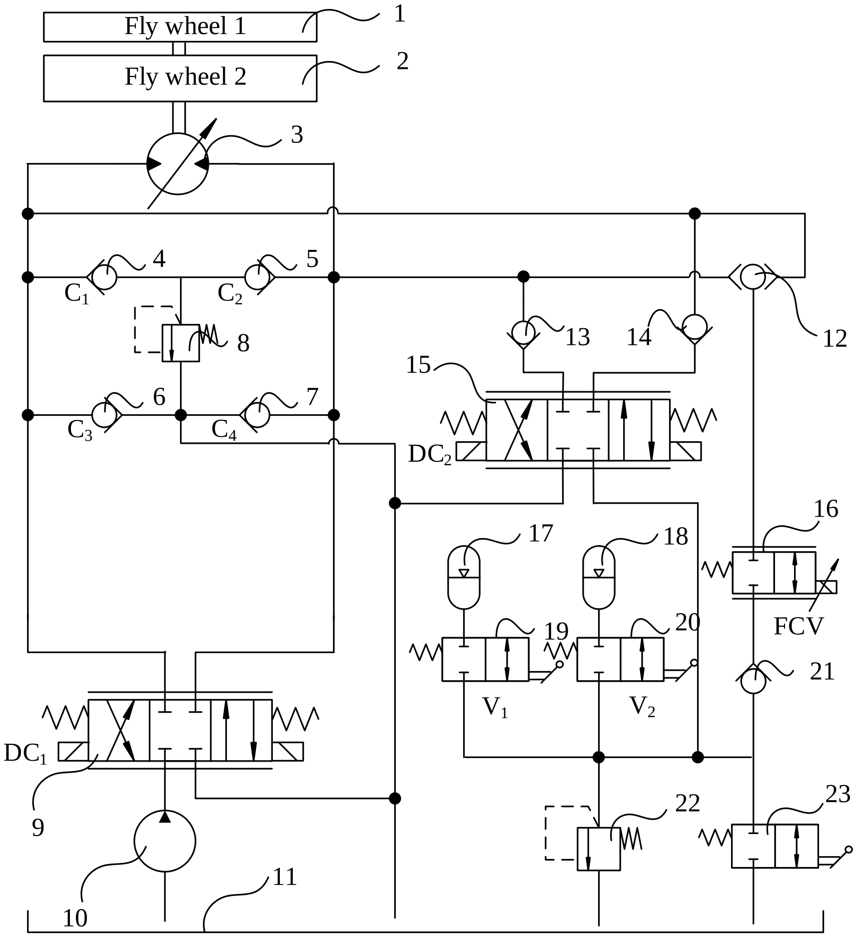

Fig. 3.8 *Hydrualic circuit of the test bench*

Table 3.1 *Components of the test bench*

1	Fly wheel 1	13	Check valve
2	Fly wheel 2	14	Check valve
3	Hydraulic motor	15	Directional valve DC2
4	Check valve C1	16	Flow control valve
5	Check valve C2	17	Accumulator 1
6	Check valve C3	18	Accumulator 2
7	Check valve C4	19	Valve V1
8	Relief valve	20	Valve V2
9	Directional valve DC1	21	Check valve
10	Hydraulic pump	22	Relief valve
11	Tank	23	Manual valve
12	Shuttle valve		

Table 3.2 *Parameters of the key components of test bench*

Component	Value	Remark and unit
Flywheel	8.985	Moment of inertia (Kgm2)
Hydraulic pump	12	Displacement (mL/r)
Hydraulic motor	28	Maximum displacement (mL/r)
Accumulator	4*2, 20	Volume (L), Pre-charge pressure (bar)
Electric motor	7.5	Rated power (kW)
Relief valve R1 and R2	350	Relief pressure (bar)
Proportional flow control valve	45	Maximum flow rate (L/min)

The hydraulic accumulator size is a key parameter of the proposed system. The common working pressure of the system is about 100 bar to 200bar. During fast acceleration and deceleration, the pressure can research to 300 bar. The hydraulic accumulator should regenerate energy with a wide range of initial pressure of accumulator. The principles of hydraulic accumulator design are shown below:

1. The hydraulic accumulator should have the ability to regenerates the energy with 200 bar of initial accumulator pressure.
2. The finial pressure of accumulator should be less than 300 bar in energy regeneration mode, with 200 bar of initial accumulator pressure.

The lower initial accumulator pressure, the lower final pressure of changing. 200 bar is the highest pressure of system in common conditions. Normally, the pressure of hydraulic accumulator is less than 200 bar after energy reused. If the hydraulic accumulator could regenerate energy with 200 bar of initial accumulator pressure, the hydraulic accumulator could regenerate energy with lower initial accumulator pressure. Hence, the hydraulic accumulator could regenerate energy with a wide range of initial pressure. That is the reason to propose the principle 1.

The finial pressure of accumulator should be less than 300 bar during charging. If the pressure of accumulator researches 300 bar in energy regeneration, the system cannot regenerate more energy. Because the maximum pressure of the system is about 300 bar. Hence, the hydraulic accumulator cannot regenerate the energy fully. If the initial pressure of accumulator is 200 bar, and finial pressure of hydraulic accumulator is 300 bar, the finial pressure of accumulator will be always lower than 300 bar in condition of lower initial accumulator pressure. Because, the lower initial accumulator pressure, the lower finial pressure of accumulator with the same charging energy.

Based on the two principles and the explications accordingly, the hydraulic accumulator should be large enough to satisfy the above principles. However, large hydraulic accumulator means high cost. If the hydraulic accumulator is very large, the pressure increase will be small. Then, the energy is hard to be reused. Hence, the smallest size of hydraulic accumulators should be chosen in condition of satisfaction of the two principles. Hence, 8-liter hydraulic accumulator is chosen among the commercial products.

In order to test the variable accumulator control strategy. The 8-liter hydraulic accumulator is divided to two 4-liter hydraulics accumulators. The manual valves are installed in the system to control the connection of each accumulator to the system. Hence, both two hydraulic accumulators and one hydraulic accumulator can be connected to the system based on the control strategy, which will be discussed in the chapter 4.

The flywheel inertia is selected based on a 5-ton excavator. In the testbench, the flywheel inertia is 8.985 Kgm^2 and connects to the hydraulic motor directly without gear. In the real swing system, the upper structure connects to the hydraulic motor through a gear, in which the gear ratio is about 1:100 to 1:200. Hence, the estimated upper structure inertia is 898.5 Kgm^2 to 1,797 Kgm^2, based on the inertia of the testbench. The swing part inertia of a real 5-ton excavator is about 1,000 Kgm^2 to 1,800 Kgm^2. Hence, the estimated inertia of the testbench matches well that of the real 5-ton excavator.

3.3 Chapter summary

This chapter describes the configurations and working principle of the proposed energy saving swing system. In this system, the two hydraulic independent accumulators are used as ESU. The variable hydraulic motor and FCV are installed in the system to regulate the flow rate of the accumulator and improve the system performance. The working principles of energy regeneration mode and energy reuse mode are introduced. The structure of the testbench is presented and the parameters design is discussed.

Chapter 4. CONTROL STRATEGY DESIGN

The control strategy is very important of the proposed system to improve the energy saving efficiency and system performance. In this section, the control strategy design is divided into two parts: energy regeneration and energy reuse. In energy regeneration mode, the valves control, HMD control, FCV control and working accumulator control are discussed. In energy reuse mode, the flow of accumulator control is presented. The proposed control strategy aims to improve the energy regeneration efficiency and reduce the fluctuation of the swing part.

4.1 Control strategy design of the energy regeneration

4.1.1 Analysis of the system in energy regeneration mode

During deceleration of swing system, the kinetic energy of the flywheel can be regenerated and saved in the hydraulic accumulator. In this process, the directional control valves DC_1 and DC_2 are closed and valve V_1 and V_2 are controlled to select the working accumulator, in which one accumulator or both two accumulators can work based on the control strategy. Hence, the fluid from the hydraulic motor flows to the working accumulator through the flow control valve (FCV), which controls the flow rate of the hydraulic accumulator.

During deceleration, there are several factors affect the speed of the swing part. The dynamic equation of the swing part is shown in equation 4.1:

$$J\dot{\omega} = T_{\mathrm{dec}} + T_{\mathrm{f}} + T_{w} \tag{4.1}$$

where J is the moment of inertia of the flywheel, ω is the speed of the flywheel, T_{f} is the coulomb friction torque, T_{w} is the torque of wind resistance, and T_{dec} is the deceleration torque of the hydraulic motor, which is shown in equation 4.2.

$$T_{\mathrm{dec}} = \frac{p_{ho} D}{2\pi} \eta_{\mathrm{m}} \tag{4.2}$$

where p_{ho} is the pressure of the output side of the hydraulic motor, D is the displacement of the hydraulic motor, and η_{m} is the torque efficiency of the hydraulic motor.

In equation 4.1, the friction torque, wind resistance torque and deceleration torque of hydraulic motor decelerate the swing part of excavator in deceleration mode. The frication torque comes from the mechanical components, such as the bearing. The wing resistance comes from the large volume of the actuators, such as the boom, arm and bucket. The deceleration torque of the hydraulic motor is discussed in equation 4.2. The HMD affects the flywheel speed based on equation 4.1 and 4.2. The deceleration torque can be increased with increase of the HMD and vice versa. Hence, the control of HMD is important to control the flywheel speed. In another aspect, the efficiency of hydraulic motor is variable based on the different HMD. Hence, both system performance and regenerated energy are affected by the control of HMD. The wind resistance is existed in the real excavator swing system. Compared with the deceleration torque, the wind resistance affects the speed of flywheel slightly. This factor is not considered in the experiment. The flywheel is set up in the test bench instead of real upper structure of the excavator without wind resistance.

The orifice of the FCV also affects the system performance, which can be seen in equation 4.3.

$$Q_a = C_{\mathrm{d}} A \sqrt{\frac{2(p_{ho} - p_{\mathrm{a}})}{\rho}} \tag{4.3}$$

where Q_{a} is the flow rate through the FCV, p_{a} is the pressure of the output port of the orifice, A is the orifice area of the valve, C_{d} is the flow coefficient, and ρ is the density of the hydraulic oil. The orifice of FCV not only affects the flow rate of FCV, but also affects the pressure of the hydraulic motor. The flow equation of the chamber between the hydraulic motor and FCV can describe the relation, which is shown in equation 4.4.

$$\frac{V_1}{\beta_e}\frac{\mathrm{d}p_{ho}}{\mathrm{d}t} = Q_h - Q_a \tag{4.4}$$

where V_1 is the volume of the chamber, β_e is the effective bulk modulus of hydraulic oil, Q_h is the flow rate form the hydraulic motor.

The FCV orifice controls the flow through the FCV, based on equation 4.3. If p_{ho} and p_a are constant value, the flow rate Q_a is decided by the orifice control of FCV. The volume of the chamber between the hydraulic motor and FCV is a constant value. Hence, the pressure of this chamber is controlled by the flow input from the hydraulic motor and the flow output from the FCV. The HMD controls the input pressure of this chamber, and orifice of FCV controls the output pressure of this chamber. Hence, the pressure of this chamber is decided by the control of HMD and FCV. The pressure of output port of hydraulic motor is same to the pressure of the chamber between the hydraulic motor and FCV. So, the deceleration torque is controlled by the HMD and FCV, based on equation 4.1 to 4.3.

The throttling loose of the FCV is also needed to be considered in control strategy design, because most of the energy is lost here in energy regeneration mode. The FCV control affects the energy regeneration and system performance.

Based on the above analysis, the control of HMD and FCV is very important in this system. A suitable control strategy should be developed to improve the energy regeneration efficiency and ensure the system performance. Hence, the control of the HMD and FCV should follows the following rules:

1. The system performance should be ensured.

2. The energy regeneration efficiency should be improved.

4.1.2 Control of HMD

Hydraulic systems are complex and contain nonlinearities. The nonlinearities are mainly caused by flow-pressure characteristics, orifice area openings, variations of the fluid volume under compression, cavitation and friction. Hence, the controller design of hydraulic system is difficult. Furthermore, the varied pressure, flywheel speed and inertia also affect the control performance of the controller.

Conventional proportional integral derivate (PID) controller is widely used in industry. The conventional PID controller is easy to be designed and to utilize in engineering. But the control performance is not good in nonlinearities' system. The fuzzy logic is a technology used for developing the intelligent control. The parameters of PID controller can be adjusted by the fuzzy logic intelligently, based on the fuzzy rules. It is an effective method to control the system with nonlinearities, time delay and change in system parameters[45], [46].

Therefore, a fuzzy-PID controller is chosen to be used in the proposed system to control the HMD, in which the PID parameters are tuned by the fuzzy inference in equation 4.5:

$$u_{\mathrm{m}}(t) = K_{\mathrm{p}} e(t) + K_{\mathrm{i}} \int_0^t e(t)\mathrm{d}t + K_{\mathrm{d}} \frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{4.5}$$

where $e(t)$ is the error between the reference value and real speed of the flywheel, $de(t)$ is the derivation of error, $u_{\mathrm{m}}(t)$ is the control signal of the displacement of the hydraulic motor, K_{p} is the proportional gain, K_{i} is the integral gain, and K_{d} is the derivative gain. The Fig. 4.1 shows the structure of the fuzzy-PID controller. The reference speed of the flywheel is calculated from the joystick signal. The real speed of flywheel is measured as a feedback signal to the controller. The error of the reference speed and measured speed is the input signal of the fuzzy-PID controller.

The control command of HMD is the output signal from the controller. Then, the HMD is controlled to ensure the flywheel speed follows the reference signal. The detailed fuzzy-PID scheme is shown in Fig. 4.2.

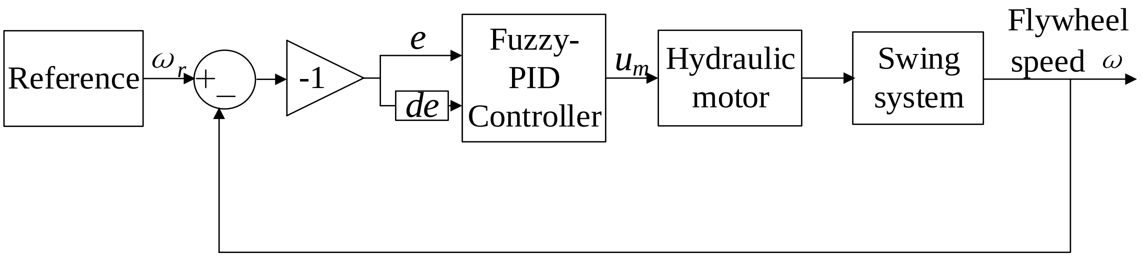

Fig. 4.1 *Structure of the control algorithm*

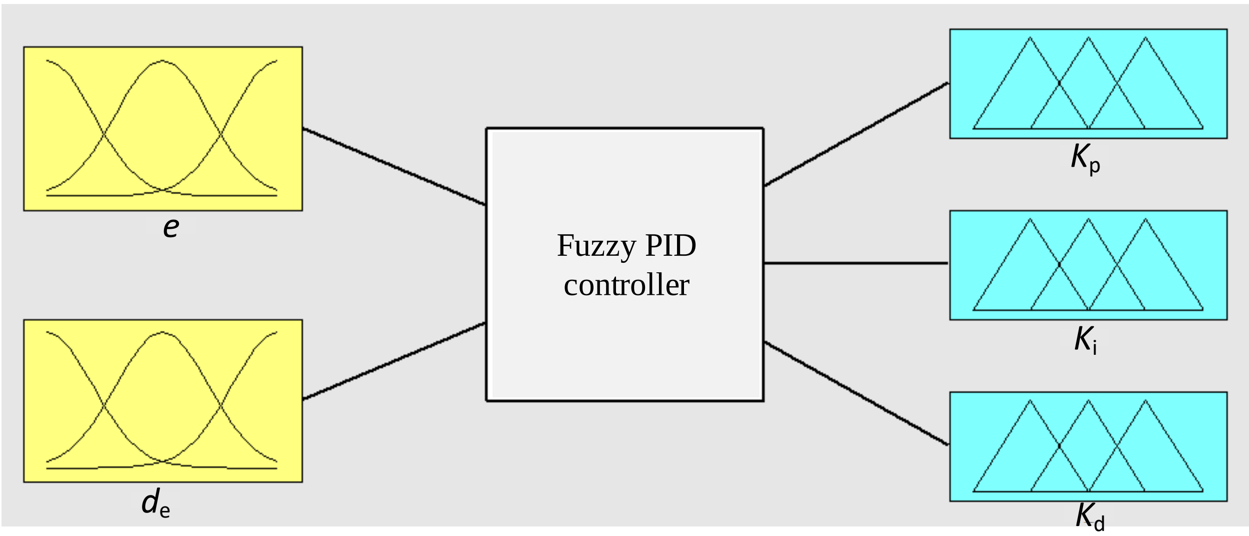

Fig. 4.2 *Fuzzy-PID inference block*

There are two inputs to the controller: the absolute value of the error |*e(t)*| and the absolute value of the derivative of the error |*de(t)*|. These two inputs are obtained from the absolute values of the system error and its derivative through the chosen gains. The details of the fuzzy inputs' membership functions are shown in Fig. 4.3

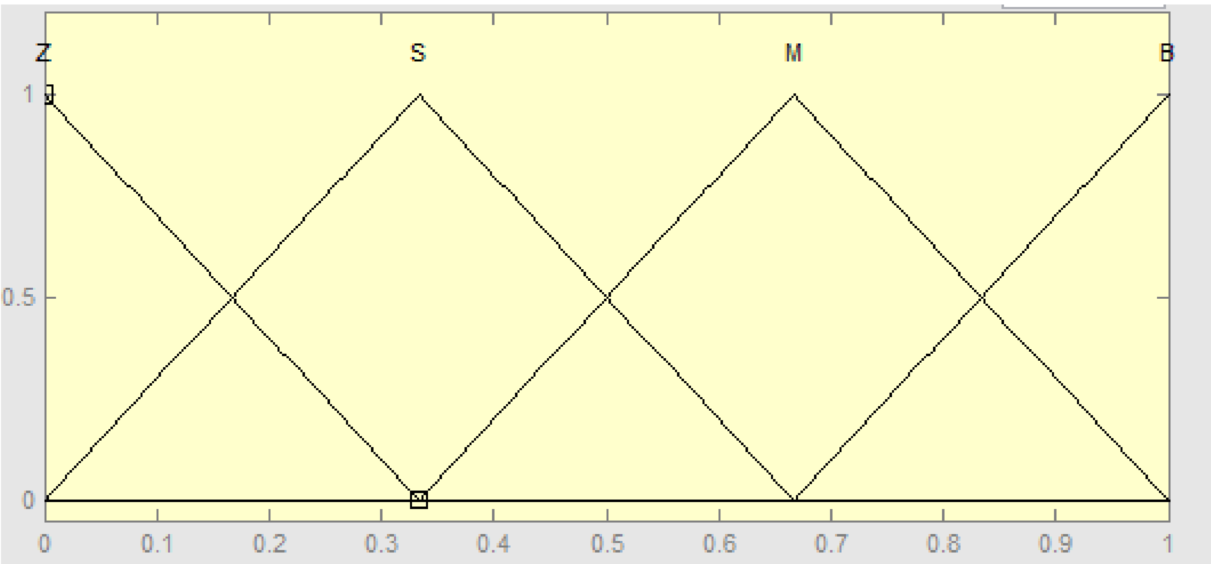

Fig. 4.3 *Fuzzy-PID membership functions for e(t), de(t)*

There are three outputs of the fuzzy set: k_p, k_i and k_d. The membership functions for each output are shown in Fig.4.4. The "centroid" method is used for defuzzification to obtain k_p, k_i, and k_d. As a result, the rule sets are established and shown in the surfaces in Fig. 4.5.

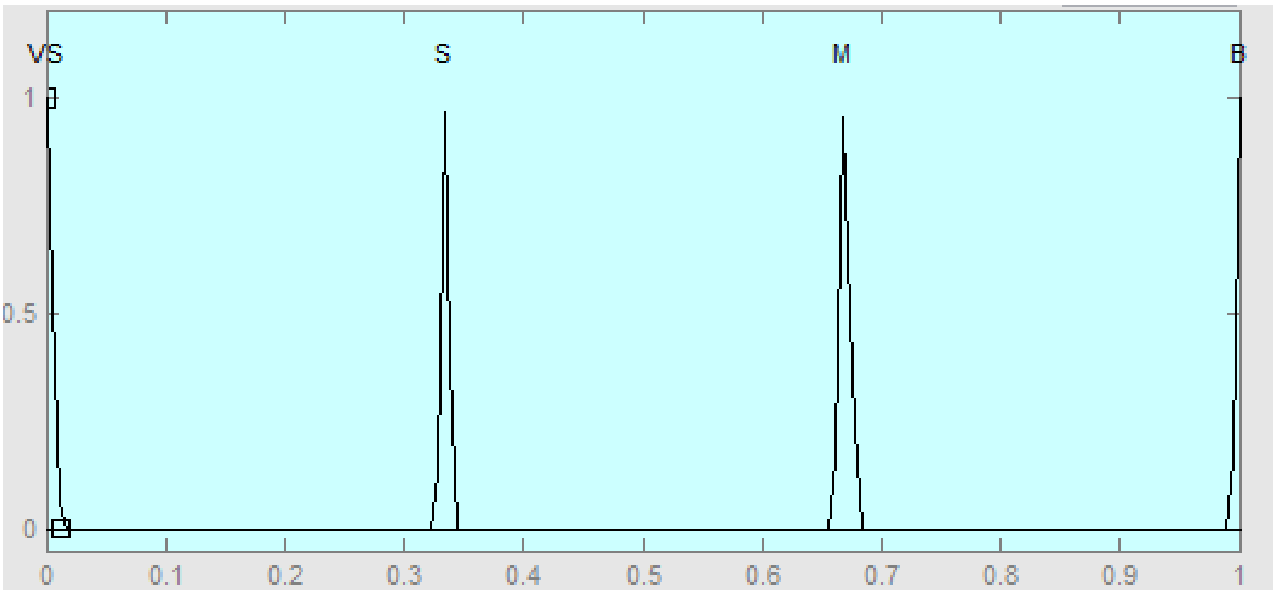

Fig. 4.4 *Fuzzy-PID membership functions for k_p, k_i and k_d*

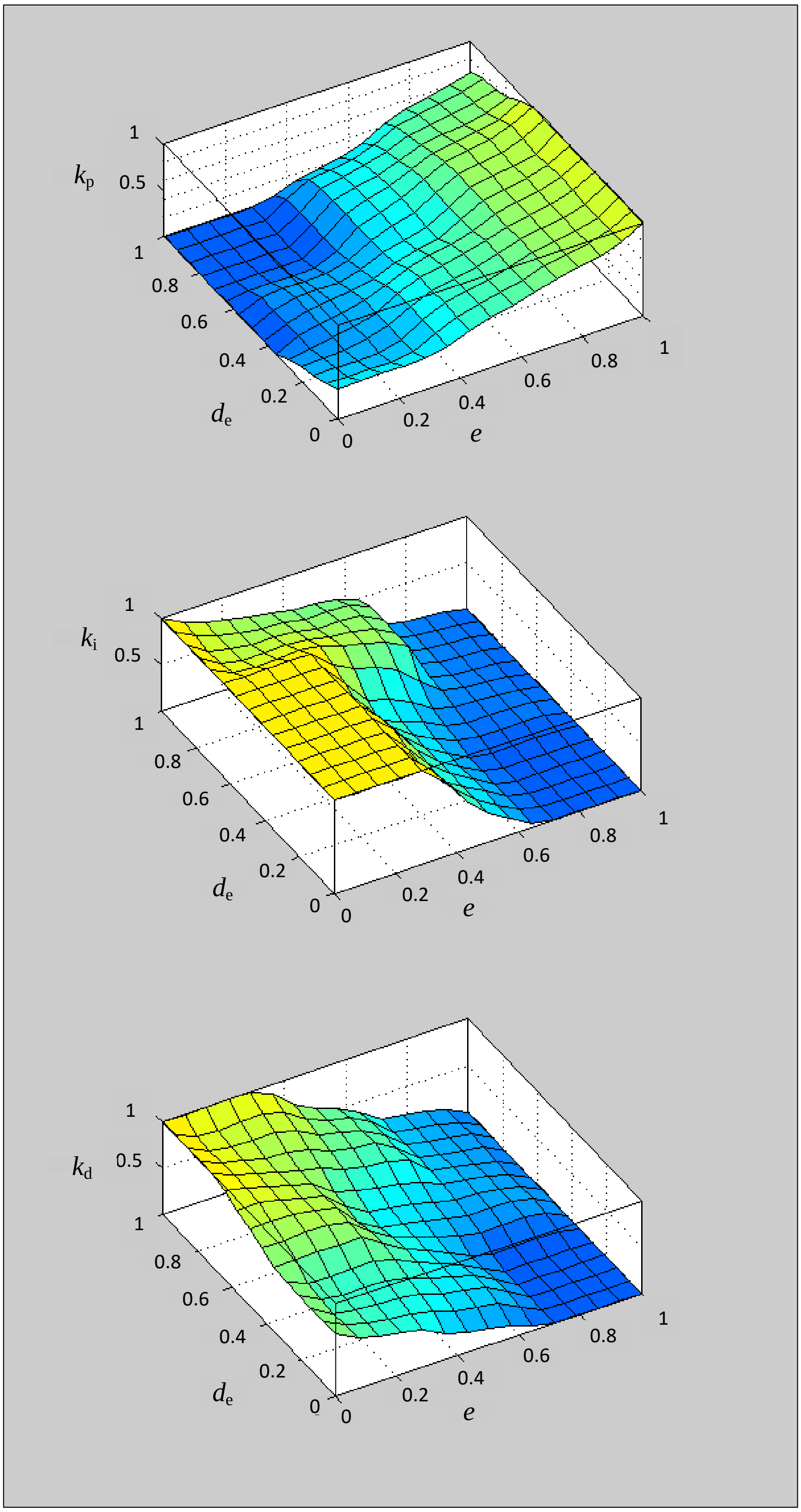

Fig. 4.5 *3D rule view of k_p, k_i and k_d*

The ranges of each outputs are from 0 to 1. The gains of each parameters of k_p, k_i and k_d are chosen and are showed in equation 6.

$$\begin{cases} K_p = G_{kp} k_p \\ K_i = G_{ki} k_i \\ K_d = G_{kd} k_d \end{cases} \tag{4.6}$$

where G_{kp}, G_{ki} and G_{kd} are the gains of each outputs, which are chosen from the experiments. Finally, the PID parameters of K_p, K_i and K_d are obtained.

Based on the above discussion of fuzzy-PID controller. The parameters of PID controller is adjusted by the fuzzy rule intelligently. Hence, the fuzzy-PID controller can provide better performance than the conventional PID controller. In the design of fuzzy- PID controller, the rule of fuzzy logic and parameter gains are designed by experiments to satisfy the performance requirement in total working conditions.

At the beginning of deceleration, the valve DC_1 is closed. Then the pressure of the output side of the hydraulic motor increases quickly. In order to avoid fluctuation of flywheel, the control command of the hydraulic motor is set to a small value 0.4 for a period. Then the fuzzy-PID controller works to control the hydraulic motor. The detail will be discussed in the following sections.

4.1.3 Combined control of HMD and FCV

Only HMD control is not enough to ensure the system performance, because the flow through the FCV also has much affection of the flywheel speed. On the other hand, the throttling loss of FCV is the largest factor that affects the energy regeneration efficiency. Large orifice of FCV can reduce the throttling loss to improve the energy regeneration efficiency. For the hydraulic motor, the larger HMD, the higher efficiency of hydraulic motor[17]. However, the FCV and HMD cannot always work at largest value, because the system performance should be considered.

Ether increase of HMD or decrease of FCV orifice can increase the deceleration torque and vice versa. Hence, there are infinite combination of HMD and FCV orifice can be chosen in a condition of specific deceleration torque. But, the efficiency of the hydraulic motor and throttling loose of FCV are different with different combination of HMD and FCV orifice. Hence, the HMD and FCV should be controlled together to improve the efficiency of both components with the specific performance requirement. Based on above analysis, the combined control of HMD and FCV (CCHF) is proposed, and structure of the control algorithm is shown in Fig.4.6. The hydraulic motor controls the performance of the system mainly. Hence, a fuzzy-PID controller is used to control the hydraulic motor.

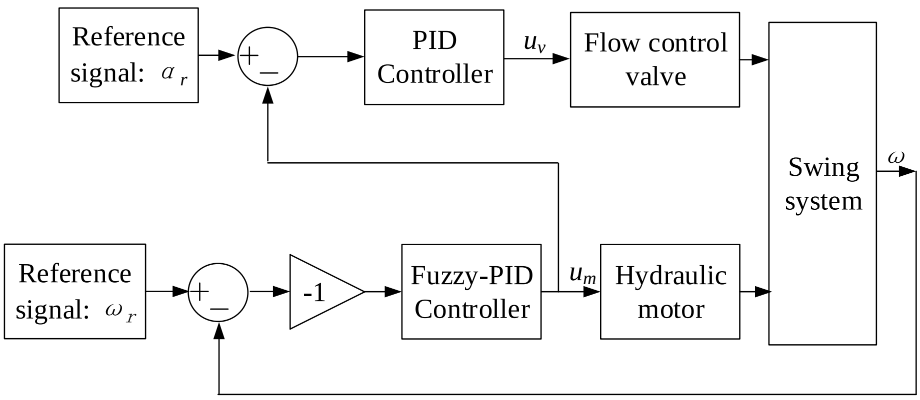

Fig. 4.6 *Structure of the CCHF*

In Fig. 4.6, u_v and u_m are the control command of FCV and hydraulic motor. The hydraulic motor control is same as the control algorithm in Fig.4.1. The FCV control is based on the error of reference signal α_r and hydraulic motor control command u_m. α_r is a reference displacement ratio that decide the reference HMD in equation 4.7.

$$D_r = \alpha D_{\max} \tag{4.7}$$

where D_{max} and D_r are the maximum HMD and reference HMD and α is a displacement ratio can be controlled. The rang of α_r is 0 to 1. 1 means the reference HMD is the maximum value. In this paper, α_r is set to 0.95, which is a large value. It means, the target of FCV control is making the hydraulic motor works at 95% of the maximum displacement.

If the hydraulic motor works at a small displacement, the FCV will increase the orifice to increase the flow rate through the hydraulic accumulator. Then, the pressure of the output side of the hydraulic motor and deceleration torque are decreased, based on equation 4.4 and 4.2. Hence, the decreased deceleration torque leads to the increase of flywheel speed. To keep the flywheel speed to follow the reference value, the HMD increases, based on the control strategy shown in Fig.4.6. In this process, both the orifice of FCV and HMD tend to be a large value, which increases the efficiency of hydraulic motor and decreases the throttling loose of FCV. Finally, the energy regeneration efficiency can be increased.

With lots of experiments, the α_r is set to 0.95, because of the performance requirement. When the HMD is larger than 0.95, such as 1, and flywheel speed is larger than the reference speed, there is a negative input (-0.05) of the controller of FCV. Then the FCV can decrease the orifice to increase the deceleration torque and to satisfy the system performance, based on the proposed control strategy in Fig. 4.6. If α_r is set to 1, and flywheel speed is larger than the reference speed, the input of FCV controller cannot be a negative value. So, the FCV cannot decrease the orifice to satisfy the system performance. Hence, setting α_r to 0.95 can make the HMD and orifice of FCV to be a large value. This parameter design balances the energy regeneration and system performance.

At the beginning of deceleration, the pressure of the output side of the hydraulic motor increases quickly, because the DC_1 is closed. To decrease the affection of flywheel fluctuation, the

FCV is fully open for 0.2 s and α is set to a small value (0.4) for 0.3 s. Then, the CCHF is worked to control FCV and HMD.

Hence, the proposed CCHF control strategy not only considers the efficiency of hydraulic motor and throttling loose of FCV to improve the energy regeneration efficiency, but also considers system performance.

4.1.4 Variable accumulator control strategy

The hydraulic accumulator pressure is a variable during system operation. When the accumulator pressure is very low, the accumulator cannot provide enough pressure to decelerate the flywheel. The FCV must decrease the orifice to increase the pressure of the output side of the hydraulic motor, which will lead to much throttling loose of FCV. To decrease the throttling loose of FCV in low accumulator pressure and increase the energy regeneration efficiency, the variable accumulator control strategy is proposed.

Two independent hydraulic accumulators are set in the proposed system. If the pressure of accumulators is lower than a threshold value at the beginning of deceleration, the valve V_1 will be closed and V_2 will be open. Only one accumulator is worked during deceleration. Hence, the accumulator pressure can increase faster and larger than that of using two hydraulic accumulators with the same flow rate. The large pressure of hydraulic accumulator could decrease the output flow rate of the chamber between the hydraulic motor and FCV. Then, the pressure of this chamber is increased, and the deceleration torque is also increased, based on equation 4.1 to 4.4. Hence, to get the same deceleration torque, the orifice of the FCV is increased to increase the output flow rate of the chamber between the hydraulic motor and FCV. Finally, the throttling loose of FCV can be decreased and energy regeneration efficiency can be increased.

If the pressure of the accumulators is higher than the threshold value, V_1 and V_2 will be open. Two accumulators work together. When the pressure is high relatively, the orifice of FCV can be large, because the large pressure of hydraulic accumulator can provide enough deceleration torque. If the accumulator pressure is very large and the deceleration torque is larger than the requirement, the FCV will works with largest orifice and hydraulic motor will have to decrease displacement to decrease the deceleration torque. In this process, the efficiency of hydraulic motor is decreased. In this case, if the size of hydraulic accumulator is large, the accumulator pressure will increase slowly. Then the HMD can keep larger relatively with higher efficiency. In conclusion, the system efficiency can be improved to use one hydraulic accumulator in condition of low accumulator pressure and to use two hydraulic accumulators in condition of high accumulator pressure.

Hence, if the accumulator pressure is lower than the threshold value, only one hydraulic accumulator will be worked to regenerate energy. The threshold value is very important to be decided by large number of experiments to optimize the energy regeneration efficiency in different cases. In this paper, the threshold value is set to 70 bar, based on many experiment results.

In the proposed system, two hydraulic accumulators are used to test the proposed control strategy. In the application of the system in real excavator, more hydraulic accumulators can be used. Then, the threshold pressure can be deveined into several ranges to control the working numbers of hydraulic accumulators. Finally, the energy regeneration efficiency can be improved further.

4.1.5 Boundary of each control strategy

The CCHF controls the orifice of FCV and HMD to be a large value to increase the energy regeneration efficiency. If the initial pressure of accumulator is high, which can provide enough deceleration torque, the FCV can be fully open to decrease the throttling loose to the minimum value.

To improve the energy regeneration further, the boundary of each control strategy is made and shown in Fig.4.7.

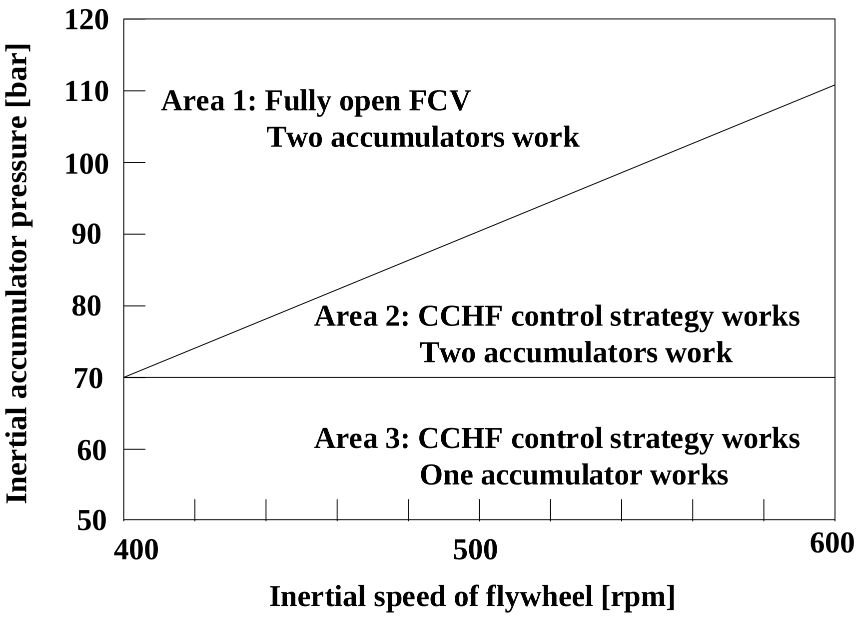

Fig. 4.7 *Boundary of each control strategy*

In the experiment, the initial flywheel speed is set to 400 rpm, 500 rpm and 600 rpm to test the energy regeneration efficiency in different speed. Because, the flywheel of testbench cannot research to higher velocity. Hence, the horizontal axis range is from 400 rpm to 600 rpm. When the flywheel starts to decelerate, the speed of flywheel and accumulator pressure can be measured by sensors. Then, the control strategy is selected based on Fig.4.7. In Fig.4.7, there are 3 areas:

Area 1: The FCV is open fully, because the initial pressure is higher relatively. In this area, when the initial speed of flywheel is low, such as 400 rpm, this control strategy can work at a low pressure of accumulator, such as 75 bar, because the required deceleration torque is small with low flywheel speed. Hence, the FCV can open fully and the pressure of accumulator can provide enough pressure to decelerate the flywheel.

Area 2: Control strategy works in condition of medium initial accumulator pressure. In this case, two accumulators can work together to regenerate the energy. The CCHF works in this case, because the accumulator pressure is not high enough to make the FCV fully open, especially in high speed of flywheel.

Area 3: The initial accumulator pressure is very low. Hence, one accumulator is worked to regenerate the energy. The CCHF control strategy is worked, because of low initial accumulator pressure.

The boundary of each control strategy is designed by experiments, which considers the energy regeneration efficiency and system performance in different inertia and deceleration time. The boundary of each control strategy is made based on the testbench. If the control strategy is sued in the real swing system, the boundary should be changed, based on the system parameters and experimental results.

4.1.6 Flow chart of the control strategy

The flow chart of the control strategy of swing deceleration is shown in Fig.4.8. The joystick signal, flywheel speed and initial accumulator pressure are measured before deceleration. Firstly, the number of working accumulators is decided based on the Fig. 4.7. Secondly, the FCV is decided to be controlled by CCHF or not is decided based on the Fig. 4.7. Next, the decided control strategy is used to control the related components. Finally, the flywheel speed is measured as the feedback signal of the controller.

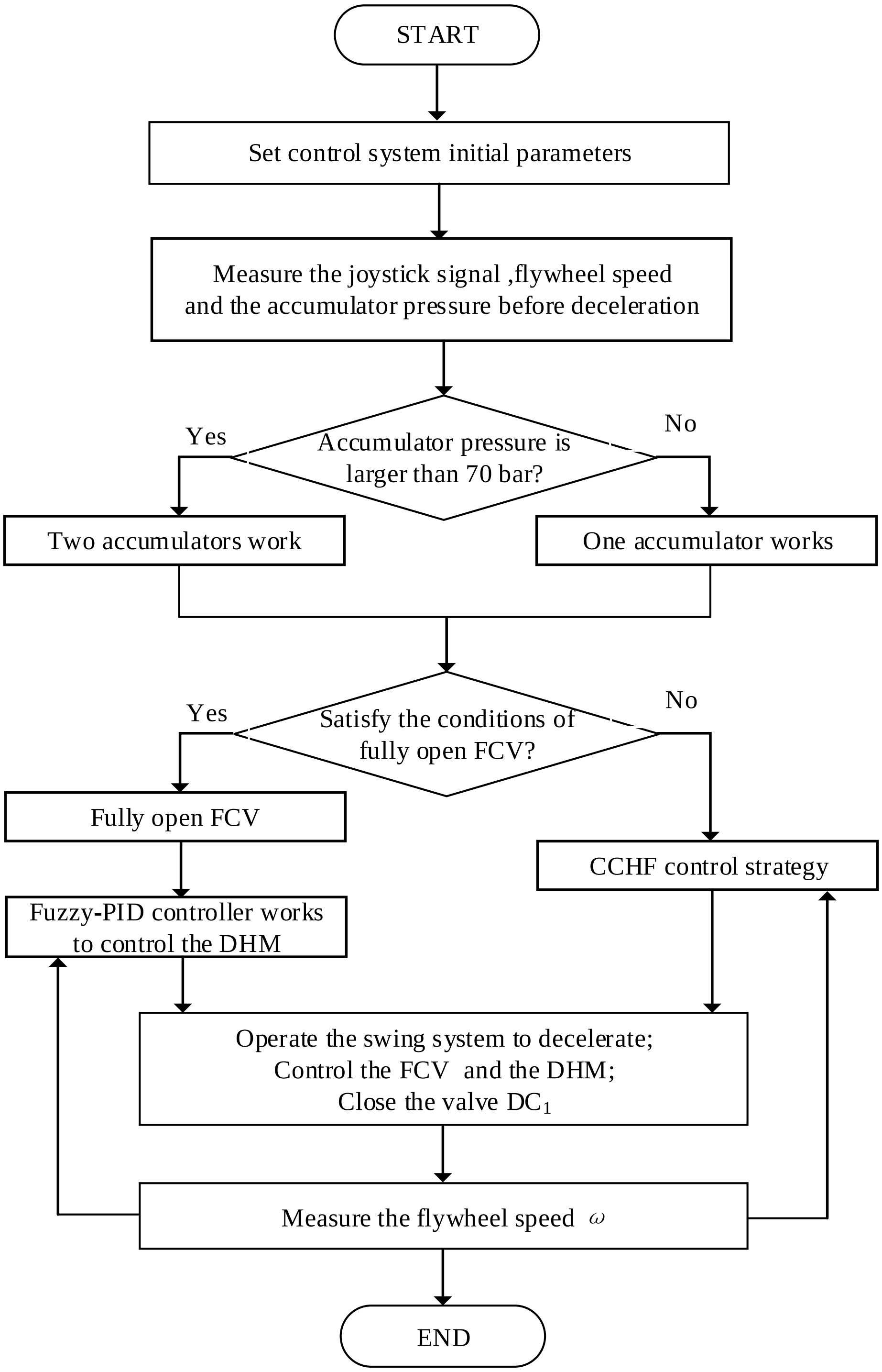

Fig. 4.8 *Flow chart of the control strategy of swing deceleration*

4.2 Control strategy design of energy reuse

In one working cycle of conventional excavator swing system, which is shown in Fig.4.9, there are three stages:

Stage 1: This is acceleration stage. In this stage, the required power of the system is large, because the large pressure is needed to accelerate the swing part. The pump provides the flow to the hydraulic motor to accelerate the swing part. The directional control valve controls the flow rate based on the joystick signal in conventional system.

Stage 2: When the target speed is got, the system works in stage 2. In this stage, the swing part keeps the target speed or has little changes of speed based on the joystick command. The energy consumption is much smaller than that of stage 1. The flow rate is also controlled by the directional valve based on the joystick signal.

Stage 3: In this stage, the swing part is in deceleration process. The output port of hydraulic motor is connected to the tank. But the flow rate of the output port of the hydraulic motor is controlled based on the joystick signal. If the swing part approaches to stop or the system needs emergency stop, the directional valve will be closed. Then, the maximum deceleration torque is generated to brake the swing part. Hence, in this process, the conventional swing system cannot regenerate the energy.

The proposed system could regenerate the energy in stage 3. The stored energy can be reused in stage 1 or stage 2. But, the regenerated energy in one cycle is not enough to drive the system in stage 1 of next cycle. Because, there is energy loose during energy regeneration process, such as throttling loss of FCV, leakage of hydraulic motor and frictional loss of mechanical components. Hence, the regenerated energy is lower than the potential kinetic energy of the flywheel. The regenerated energy is not enough to run the system in stage 1 of next cycle independently. In another aspect, the energy consumption is higher than the kinetic energy of the flywheel of state 1. Because, there is energy loose in acceleration process.

In conclusion, the regenerated energy in state 3 of one cycle is not enough to drive the flywheel to work in stage 1 of next cycle. There are two methods to reuse the regenerated energy in the next cycle.

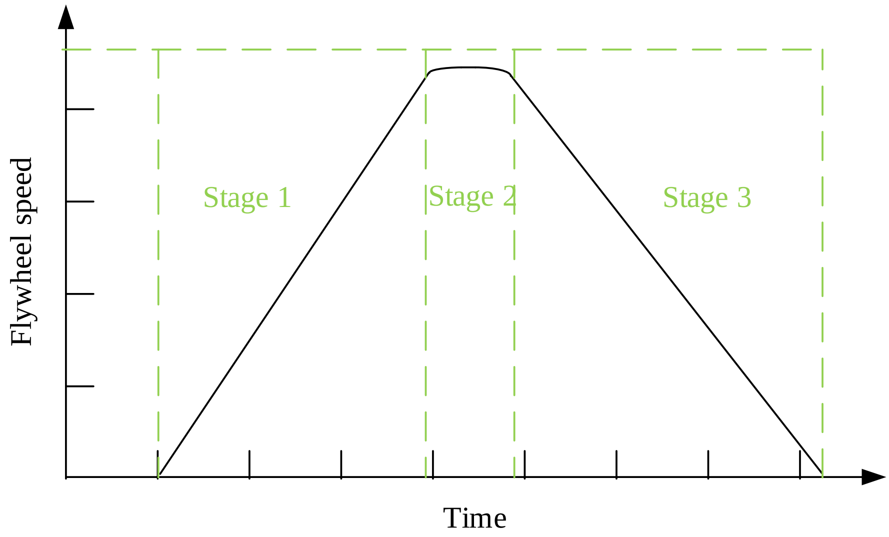

Fig. 4.9 *Onc cycle of swing system operation*

One idea is that both hydraulic pump and accumulator provide the flow to run the flywheel. Then the energy consumption of the pump will be reduced. But it is very difficult to realize, because the flow from the hydraulic pump should be governed by valve control, variable hydraulic pump control or engine speed control. The method of valve control may lead to additional energy loos. Utilization of variable hydraulic pump may increase the cost of system. Then pump efficiency is also decreased with decrease of displacement of pump. Engine speed control may lead to decreases of engine efficiency.

Another idea is using multiple cycles of regenerated energy to accelerate the flywheel once. It means, the system stores the regenerated energy in several cycles until the energy is enough to accelerate the flywheel. Then the stored energy is reused to drive the flywheel in the next cycle. But the large size of accumulators should be installed in the system, because much energy is need in stage 1. The energy regeneration efficiency cannot be high with increases of accumulator pressure in several cycles.

Based on the above analysis, this paper plans to reuse the regenerated energy in stage 2, because there is smaller energy requirement than that of stage 1. One cycle of regenerated energy is enough to drive the system in stage 2 of next cycle.

Hence, the working principles of the proposed system in each stage are shown below:

Stage 1: The hydraulic pump provides energy to run the flywheel. The function is same as that of the conventional system.

Stage 2: The hydraulic accumulator provides the energy to the flywheel and the hydraulic pump stopes working. Compared with the conventional system, the energy consumption can be decreased in this stage.

Stage 3: The system works in energy regeneration mode. The control strategy is shown in section 4.10.

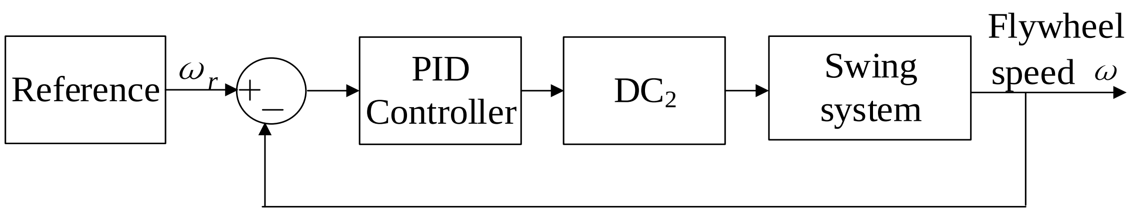

Fig. 4.10 *Structure of control algorithm of DC_2 in stage 2*

In stage 2, the directional valve DC_2 should be controlled to regulate the flow through the accumulator. The control structure is shown in Fig.4.10. A PID controller is used to regulate the orifice of DC_2. The Reference speed is calculated from the joystick command. Hence, based on the joystick command, the flow rate of the hydraulic motor is controlled. In this stage, the DC_1 is closed and the hydraulic pump is stopped. The hydraulic motor is worked with smallest value to decrease to requirement of the flow rate.

4.3 Chapter summary

In this chapter, the control strategy of the system is designed. The CCHF is proposed to control the HMD and FCV in energy regeneration mode. The energy regeneration efficiency and system performance are considered to design the control strategy. The variable accumulator control strategy is proposed to improve the energy regeneration efficiency further. Next, the energy reuse control strategy is discussed. In this chapter, the total control strategies of the system in each working mode are designed.

Chapter 5. EXPERIMENT RESULTS AND ANALYSIS

Bases on the structure and control strategy of the proposed system tin Chapter 3 and Chapter 4, the experiment is conducted in this chapter. The performance of each proposed control strategy is verified by experiment results. The energy regeneration efficiencies are tested in different conditions. The energy saving efficiencies are tested in multiple cycles of experiments.

5.1 Experiment results and analysis of the CCHF

An experiment was done to test the CCHF control strategy. The initial flywheel speed, accumulator pressure and deceleration time were set to 500 rpm, 4 s and 66 bar. Based on Fig. 4.7, one accumulator and CCHF were worked in this experiment, in which the valve V_1 and V_2 were set by manual before deceleration. Both of flywheel 1 and flywheel 2 were connected to hydraulic motor.

The experimental results are shown in Fig. 5.1 and Fig. 5.2. The flywheel speed is shown in Fig.5.1 (a). The flywheel is almost stopped at 7 s. The flywheel cannot stop completely, because the mechanical brake is not set up in the testbench. The hydraulic brake cannot stop the hydraulic motor quickly at a low speed, such as 50 rpm, because the leakage exists, and a long rubber pipe is used in the test bench. In the real excavator, the swing part can be stopped quickly at a low speed by mechanical break. Hence, the flywheel is assumed to be sopped by the mechanical brake when the speed of the flywheel is lower than 50 rpm.

The control command of HMD and FCV are shown in Fig.5.2 (a) and (b), in which 0 to 1 of y axis means 0 to 100% of HMD and orifice of FCV. At beginning of deceleration, the control commands of FCV and HMD are set to 1 and 0.4, which are analyzed in chapter 4 to decrease the fluctuation of flywheel speed. From 3.5 s to 4.2 s, the error of flywheel speed increases. Hence, the HMD increases and FCV decreases to decrease the error. From 4.2 s to 4.7 s, the error of flywheel decreases, so the HMD is decreased based the Fuzzy-PID controller in Fig. 4.1 and Fig. 4.6. At the same time, the FCV increases to increase the HMD based on the CCHF control strategy. Finally, HMD increases to around 0.95 from 5 s to the end, and the accumulator pressure is increased to 88.1 bar in Fig. 5.1 (b).

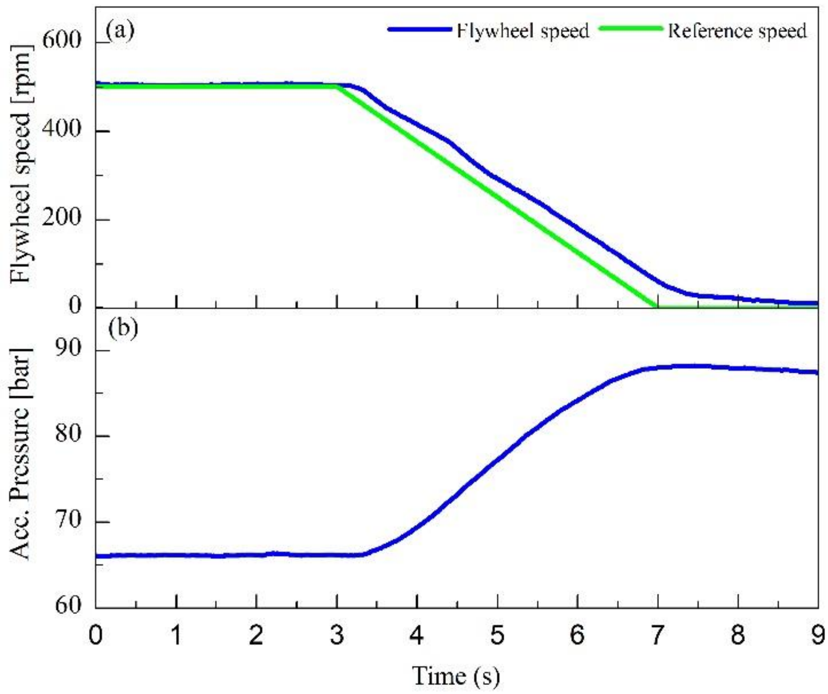

Fig. 5.1 *Experiment results of flywheel speed and accumulator pressure*

As a comparison, the experiment was done by using a constant control command of FCV. The control command of FCV is set to 0.54 which is got by lots of experiments to satisfy 4 s deceleration. The experiment results are shown in Fig.5.3 and Fig.5.4. Even though the HMD is got the minimum value from 3.5 s to 4.2 s, the FCV cannot be adjusted. Hence, the flywheel speed has a fluctuation, and the small HMD leads to lower hydraulic motor efficiency. The FCV of CCHF is much larger than 0.54 from 3 s to 6 s and a little smaller than 0.54 from 6 s to the end. In most of time, the orifice of FCV of CCHF is larger than that of constant FCV control strategy, so the throttling loose is lower with CCHF control strategy. The accumulator pressure increased to 79.6 bar in Fig.5.3 (b). The regenerated energy of each control strategy is shown in table 2.

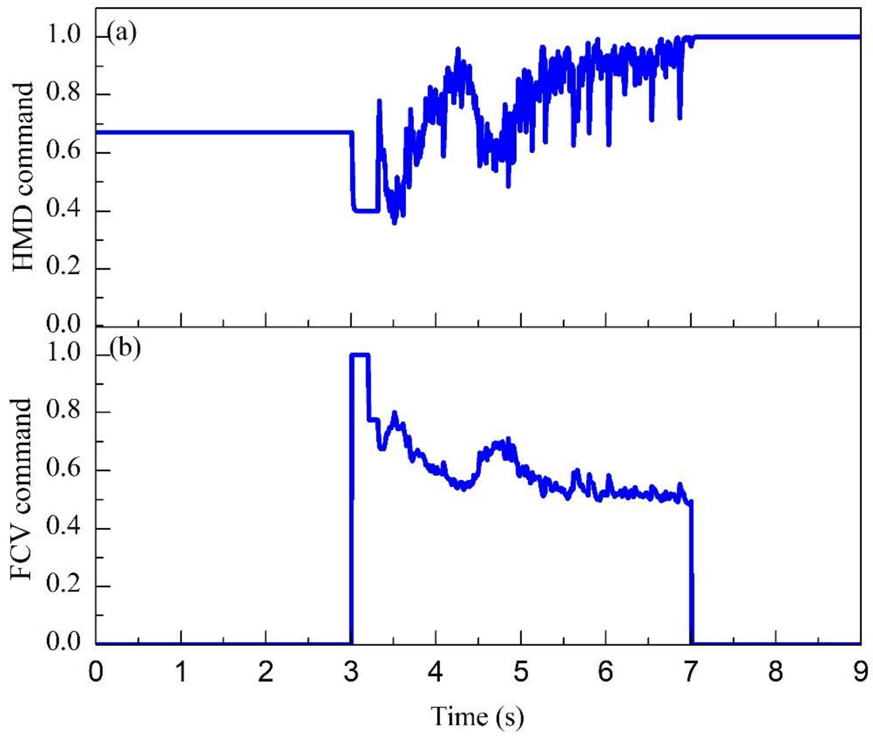

Fig. 5.2 *Experiment results of control command of HMD and FCV*

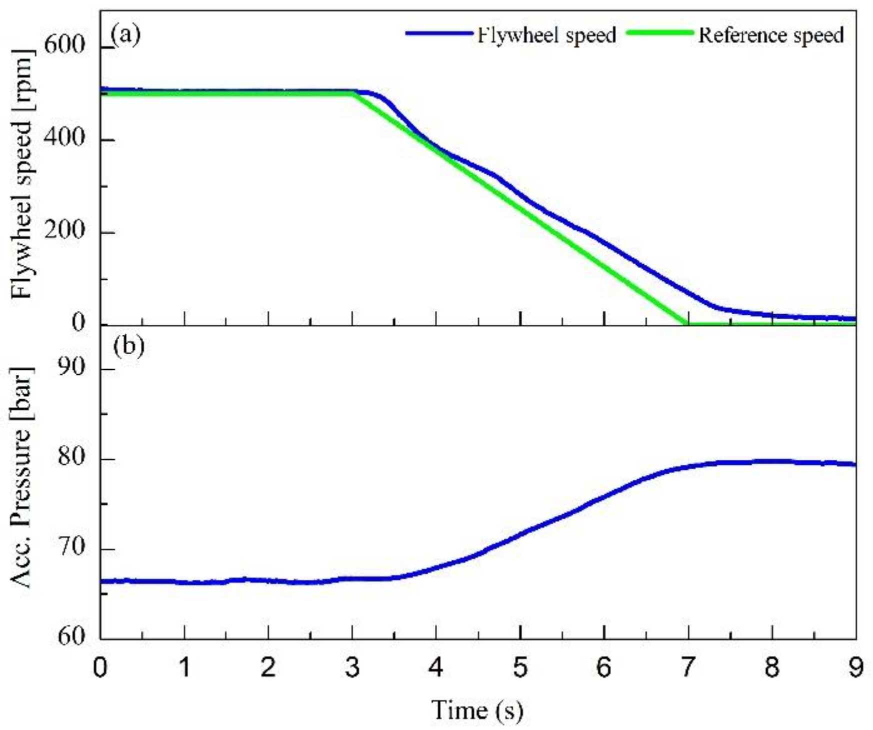

Fig. 5.3 *Experiment results of flywheel speed and accumulator pressure*

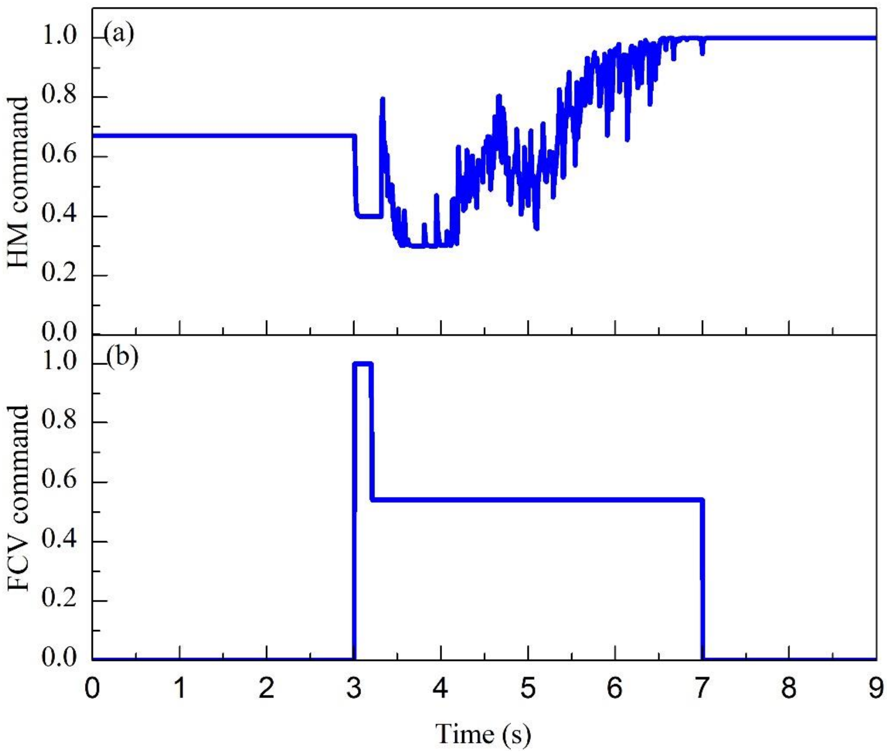

Fig. 5.4 *Experiment results of control command of HMD and FCV*

Table 5.1 *Regenerated energy of CCHF and constant FCV*

Controller	Regenerated energy (J)
CCHF	4791
Constant FCV	2924

In table 5.1, the regenerated energy of CCHF is much larger than that of constant FCV strategy. The improved ratio is 64%. Hence, the regenerated energy is improved, and fluctuation of the flywheel speed is decreased by using the CCHF.

5.2 Experiment of variable accumulator control strategy

The experiments were done to show the performance of the variable accumulator control strategy. The initial flywheel speed, accumulator pressure and deceleration time were set to 400 rpm, 4 s and 50 bar. The inertia accumulator pressure is set by manual setup, so there is a little error. Both of flywheel 1 and flywheel 2 were connected to hydraulic motor.

Based on the variable accumulator control strategy and Fig.4.7, 1 accumulator was worked in system, and the experiment results are shown in Fig.5.5 and Fig. 5.6 with blue color. As a comparison, an experiment was done which used conventional constant accumulator strategy with two accumulators and the experiment results are shown in Fig. 5.5 and Fig. 5.6 with green color.

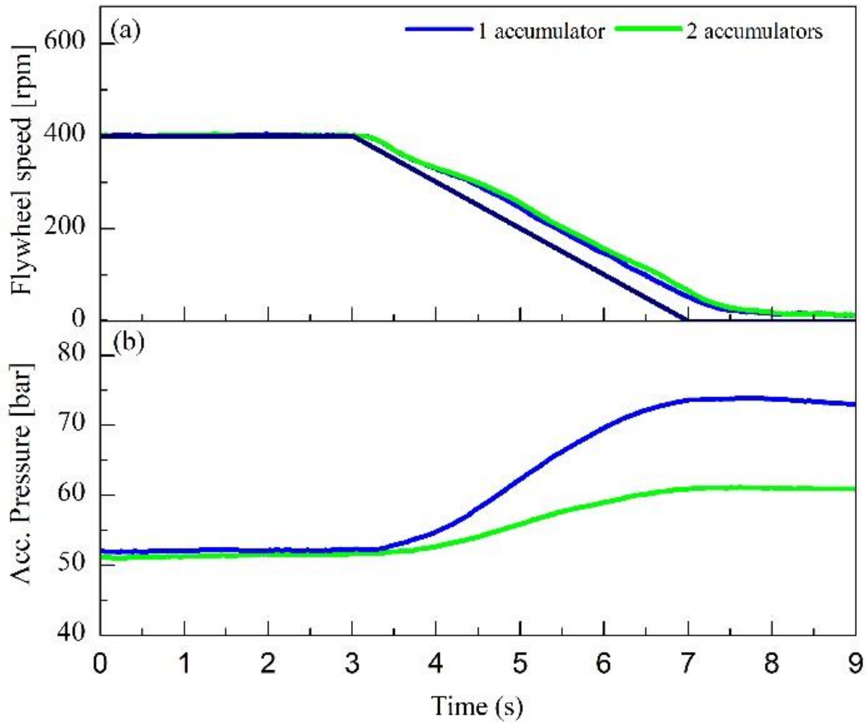

Fig. 5.5 *Experiment results of flywheel speed and accumulator pressure*

The flywheel speeds of two experiments are shown in Fig.5.5 (a). The results are almost same with the two control strategies. The accumulator pressure of blue curve increases faster and higher than that of the green curve in Fig.5.5 (b), because the small size of hydraulic accumulator was used in experiment, based on the variable accumulator control strategy. The higher pressure of hydraulic accumulator, the higher deceleration torque can be provided. Hence, larger control command can be used to control the FCV, which has larger orifice and lower throttling loss than that of using 2 accumulators in Fig.5.6 (b). The HMD commands of two experiments are almost same in Fig. 5.6 (a).

Finally, the regenerated energy of two experiments are shown in table 5.2. The system can regenerate more energy by using the variable accumulator control strategy. The improved ratio is 11%.

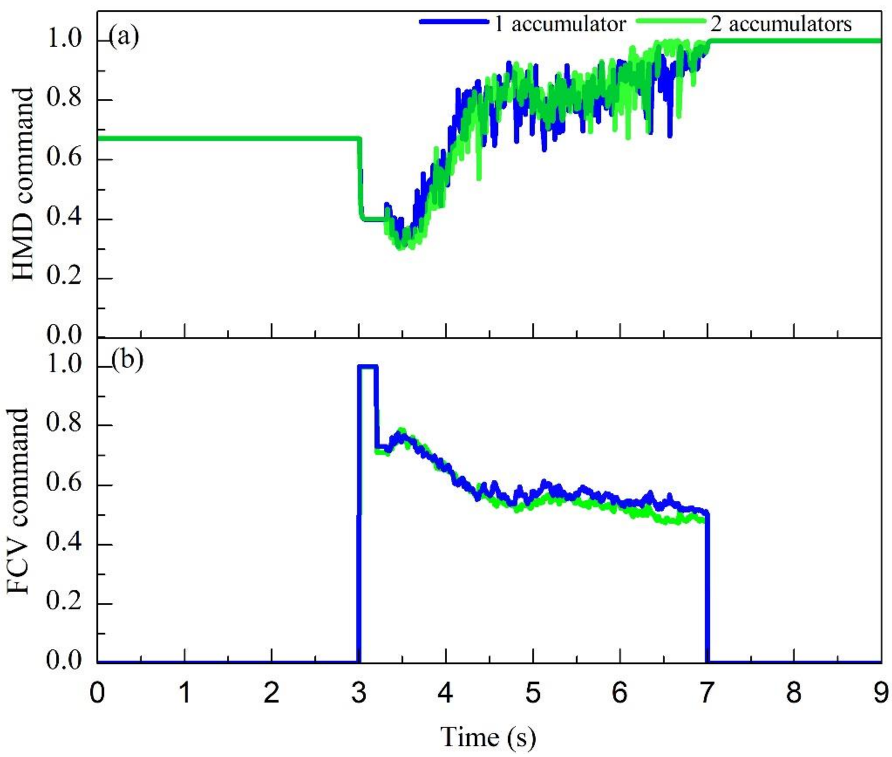

Fig. 5.6 *Experiment results of control command of HMD and FCV*

Table 5.2 *Regenerated energy of CCHF and constant FCV*

Control strategy	Regenerated energy (J)
Variable accumulator control strategy (1 accumulator)	2720
Conventional constant accumulator control strategy (2 accumulators)	2453

The regenerated energy is tested in other conditions, which are shown in table 5.3. The initial pressures of accumulator were set to 55 bar. Based on the experiment of each condition, the improvement ratio of regeneration energy is from 2% to 27%.

Table 5.3 *Regenerated energy of each condition*

Initial flywheel speed (rpm)	Deceleration time (s)	Regenerated Energy of proposed control strategy (J)	Regenerated energy of conventional control strategy (J)	Improved ratio (%)
400	3	2435	2264	8
	4	2897	2853	2
500	3	2950	2318	27
	4	4133	3849	7
600	3	3998	3618	11
	4	5595	4809	16

5.3 Experiment of energy regeneration efficiency in different conditions

In the proposed swing system, the kinetic energy of flywheel is converted into hydraulic energy and stored in the hydraulic accumulator. The hydraulic energy can be calculated in the equation 5.1.

$$E_{\mathrm{reg}} = \sum_{i=1}^{n} Q_{\mathrm{acc(i)}} p_{acc(i)} \tag{5.1}$$

where i is the index of state, E_{reg} is the regenerated energy, and $Q_{\mathrm{acc(i)}}$ and $p_{\mathrm{acc(i)}}$ are the flow rate and pressure of accumulator respectively. The gas-charged accumulator is used in the system. The flow rate of the hydraulic accumulator is equal to the rate of the gas volume change with reversed signs, which is shown in equation 5.2.

$$Q_{\mathrm{acc(i+1)}} = -\Delta \dot{V}_{\mathrm{g(i+1)}} \tag{5.2}$$

where $\Delta V_{\mathrm{g(i+1)}}$ and $Q_{\mathrm{acc(i+1)}}$ are the volume change and flow rate between state i and i+1. In the experiment, the pressure of hydraulic accumulator is measured in each sampling time. Then the volume change of accumulator in each sampling time can be calculated in equation 5.3.

$$p_{\mathrm{gi}} V_{\mathrm{gi}}^{\mathrm{n}} = p_{\mathrm{g(i+1)}} V_{\mathrm{g(i+1)}}^{\mathrm{n}} \tag{5.3}$$

where, p_{g} and V_{g} are the pressure and volume of the gas in the hydraulic accumulator, and n is the adiabatic exponent (n=1.4). The kinetic energy of flywheel can be calculated by equation 5.4.

$$E_{\mathrm{FW}} = \frac{J}{2}\left(\frac{2\pi\omega}{60}\right)^2 \tag{5.4}$$

where E_{FW} is the kinetic energy of the flywheel. The energy regeneration efficiency can be calculated by equation 5.5.

$$\eta_{\mathrm{reg}} = \frac{E_{reg}}{E_{FW}} \tag{5.5}$$

where η_{reg} is the energy regeneration efficiency. In the real swing system, the speed of swing part, accumulator pressure, deceleration time and inertia of swing part are different, in each cycle of deceleration. Hence, the experiments were done to test the energy regeneration efficiency of the proposed system with different initial accumulator pressure, initial flywheel speed, deceleration time and flywheel inertial.

Table 5.4 *Experiment results with high inertia*

Initial accumulator pressure (bar)	Initial flywheel speed (rpm)	Deceleration time (s)	Energy regeneration efficiency (%)	Serial No.
55	400	3	32	1
		4	38	2
	500	3	25	3
		4	35	4
	600	3	23	5
		4	32	6
80	400	3	53	7
		4	48	8
	500	3	36	9
		4	49	10
	600	3	27	11
		4	45	12
110	400	3	54	13
		4	47	14
	500	3	56	15
		4	51	16
	600	3	51	17
		4	51	18

In the real swing system, the deceleration time is smaller than 5 s normally. So, the deceleration time of the experiments is set to 3 s and 4 s. If the deceleration time is shorter than 3 s, the FCV will closed to provide the maximum deceleration torque to decelerate the swing part and energy will not be regenerated. This condition is not considered in this paper. The inertial speeds of flywheel were set to 400 rpm. 500 rpm and 600 rpm. The inertial accumulator pressures were set to 55 bar, 80 bar and 110 bar. The experiment results of high inertia are shown in table 5.4, in which the flywheel 1 and flywheel 2 were worked together. Table 5.5 shows the low inertia results, in which only flywheel 2 was connected to the hydraulic motor.

In condition of low flywheel speed, the energy regeneration efficiency is high, such as the experiments 1,3 and 5. When the flywheel speed is low, the required deceleration torque is low. Then, the FCV could work with a large orifice relatively, in which the throttling loose of FCV is decreased. Hence, the energy regeneration efficiency of experiment 1 is higher than that of experiment 3 and 5. This phenomenon also can be proved in experiment 2,4 and 6. But in experiment 13, 15 and 17, the energy regeneration efficiency kept in same level. Because, when the accumulator pressure is high, the FCV can always work in large orifice. The throttling loos of FCV has little changes with different initial flywheel speed. So, in these conditions, the energy regeneration efficiency is affected by other factors mainly.

In conditions of long deceleration time, the energy regeneration efficiency is high, such as the experiments 1 to 12. The efficiency is higher with 4 s deceleration time than that with 3 s deceleration time. Because the required deceleration torque is low with long deceleration time. The FCV also can work with large orifice and low throttling loose. When the initial accumulator pressure is high, the energy regeneration efficiency is not affected by the deceleration time. The reason is discussed in next paragraph.

Table 5.5 *Experiment results with low inertia*

Initial accumulator pressure (bar)	Initial flywheel speed (rpm)	Deceleration time (s)	Energy regeneration efficiency (%)	Serial No.
55	400	3	28	19
		4	23	20
	500	3	25	21
		4	26	22
	600	3	31	23
		4	31	24
80	400	3	34	25
		4	30	26
	500	3	38	27
		4	33	28
	600	3	41	29
		4	39	30
110	400	3	33	31
		4	34	32
	500	3	42	33
		4	35	34
	600	3	48	35
		4	43	36

In condition of high accumulator pressure, the energy regeneration is improved. This tendency can be got based on all the experiment results. Because the throttling loose of FCV is small with high accumulator pressure.

In most cases, low inertia has low energy regeneration efficiency, because the orifice of FCV and HMD cannot work with large value linearly. In another aspect, part of the energy loose is not decreased with the decrease of inertial accordingly, such as the frictional loose. But the total kinetic energy is decreased with low inertia. Hence, the proportion of this energy loose is increased. Based on above two reasons, low inertia has low energy regeneration efficiency in most cases. Only when the flywheel speed is large and deceleration time is short, the energy regeneration efficiency is higher relatively, such as experiment 11and 29. Because the high flywheel speed and large inertial lead to large brake torque requirement in experiment 11. Then the orifice of FCV is very small and flow rate is high. Hence, much throttling loose exists in FCV and leads to low energy regeneration efficiency.

5.4 Experiment of energy saving efficiency

The energy regeneration is discussed in section 5.3. The reuse of the regenerated energy is discussed in this section. Firstly, the definition of energy saving efficiency is discussed. Secondly, the experiments are done to show the energy saving efficiency of the proposed system. Finally, the analysis of the experiment results is presented. The energy saving efficiency is calculated based on equation 5.6.

$$\eta_{save} = \frac{E_{con} - E_{pro}}{E_{con}} \tag{5.6}$$

where, E_{con} and E_{pro} are the energy consumption of the conventional system and proposed system, respectively, and η_{save} is the energy saving efficiency. In the testbench, the hydraulic pump is driven by an electric motor. The speed sensor and torque sensor are installed to test the speed and torque of electric motor. Then the input energy of the system can be calculated in equation 5.7.

$$E_{in} = \int T\omega dt \tag{5.7}$$

where, E_{in} is the energy consumption of the electric motor, ω and T are the angular speed and torque of the electric motor and pump.

Three cycles of low inertia are tested in experiment and the results are shown in Fig. 5.7 and Fig. 5.8. The deceleration time was 4 s, 3 s and 5 s in each cycle to test the energy saving efficiency in different cycle time. The maximum flywheel speeds of each cycle are 400 rpm, 500 rpm and 560 rpm to test energy saving efficiency in different flywheel speed. The initial pressure was set to be 110 bar, which can be seen in Fig. 5.7 (b).

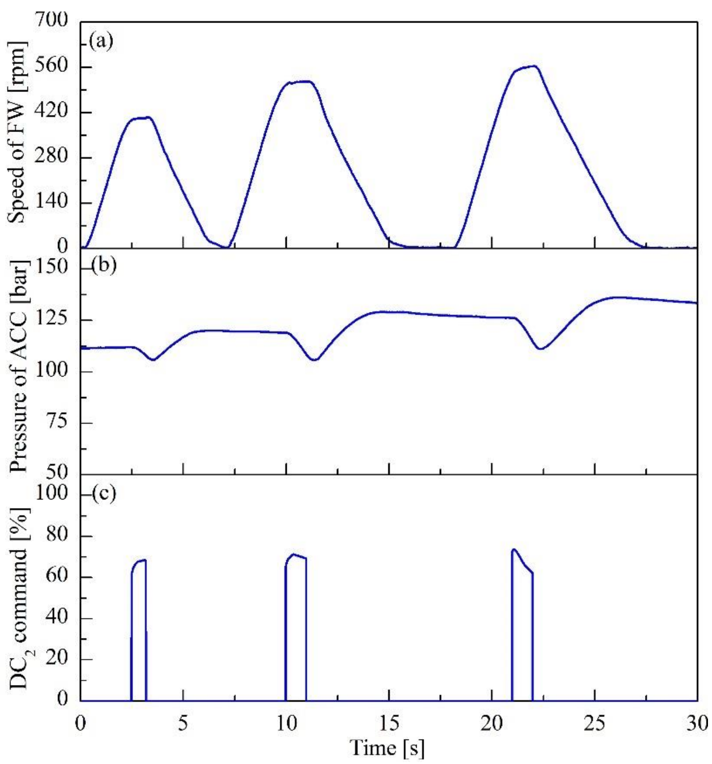

Fig. 5.7 *Experimental results of proposed system (1)*

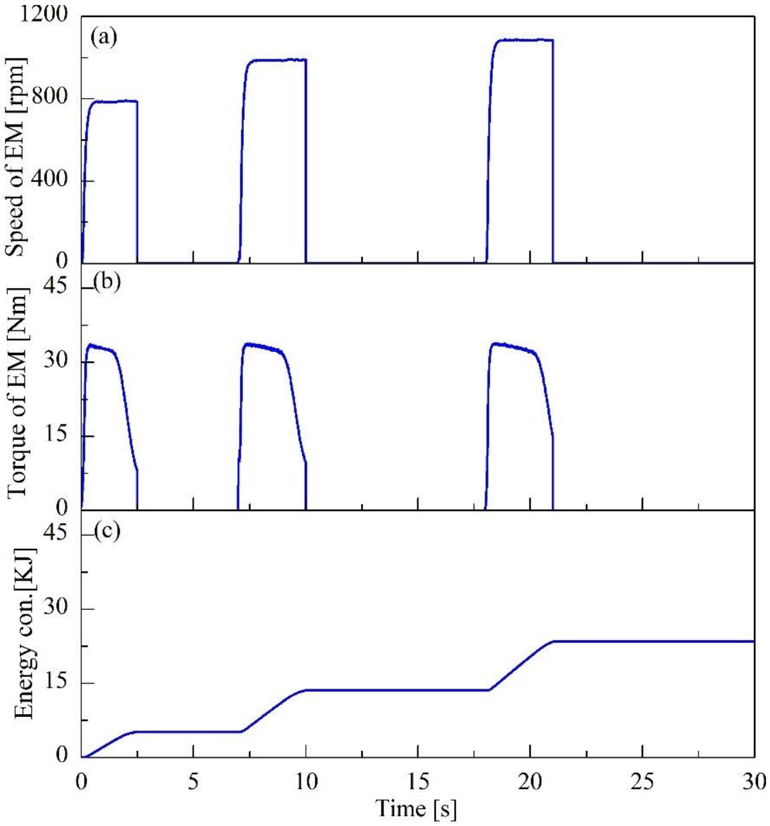

Fig. 5.8 *Experimental results of proposed system (2)*

From 1 s to 2.5 s, the electric motor drove the hydraulic pump to accelerate the flywheel to 400 rpm, and the system worked in stage 1. From 2.5 s to 3.2 s, the system worked in stage 2, which means the accumulator provided the energy to keep the flywheel running. Hence, the valve DC_2 was energized, shown in Fig. 5.7c. The electric motor was stopped in this stage. The speed and torque of electric motor becomes zero, shown in Fig. 5.8 (a) and (b). The stored regenerated energy of hydraulic accumulator is reused in this stage. There is no energy consumption of hydraulic pump. The system worked in stage 3 from 3.2 s to 6.2 s. In this stage, the accumulator stored the regenerated energy, which was same as the experiments in section 5.3. Then, the energy was reused in stage 2 of the second cycle.

Finally, the energy consumption of the three cycles was 23.4 kJ, shown in Fig. 5.8 (c). The accumulator pressure was 110 bar at beginning, and 134 bar after 3 cycles of running. Hence, the pressure was increased in accumulator where the increased energy was 3.8 kJ. This energy can be reused in the next cycle. Hence, the energy consumption is estimated to 19.6 kJ, based on equation 5.8.

$$E_{\mathrm{e}} = E_{\mathrm{in}} - E_{\mathrm{da}} \tag{5.8}$$

where, E_{e} is the estimated energy consumption of the proposed system and E_{da} is the energy difference of accumulator between the beginning of the experiment and the end of the experiment.

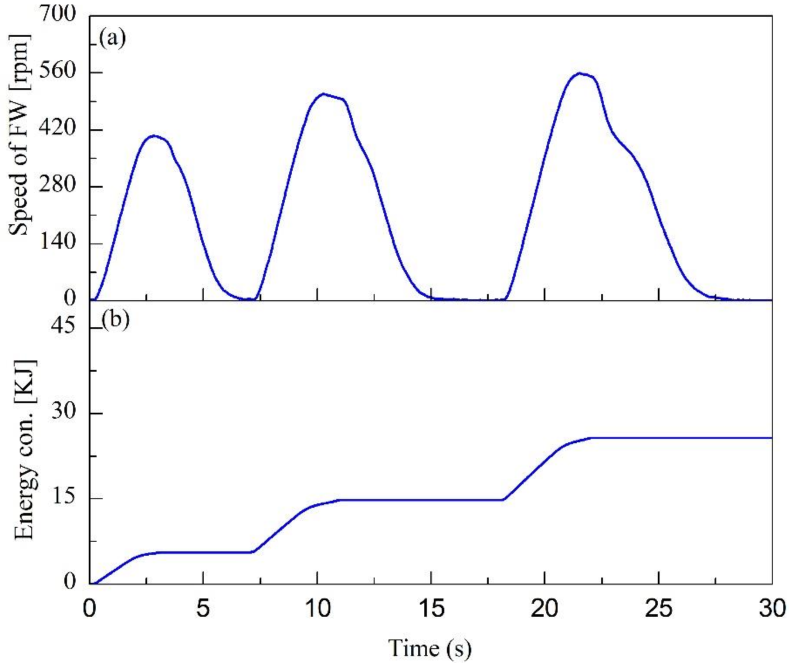

Fig. 5.9 *Experimental results of conventional system (1)*

The experiment of conventional system was also done for comparison. The manual valve 23 was set to be open in Fig. 3.8. Hence, the accumulator cannot work, and the flow goes through valve 23 and FCV to the tank during deceleration. The FCV was controlled to regulate the flow through the tank. During acceleration in stage 1, the main pump provided the energy to the flywheel, in which the function was same as the proposed system. In stage 2, the pump also provided energy to run the flywheel, which was different from that in the proposed system. In stage 3, the proposed system does not regenerate the energy. The experimental results of conventional system are shown in Fig. 5.9 and Fig. 5.10. The profile of flywheel speed is the same as that of proposed system.

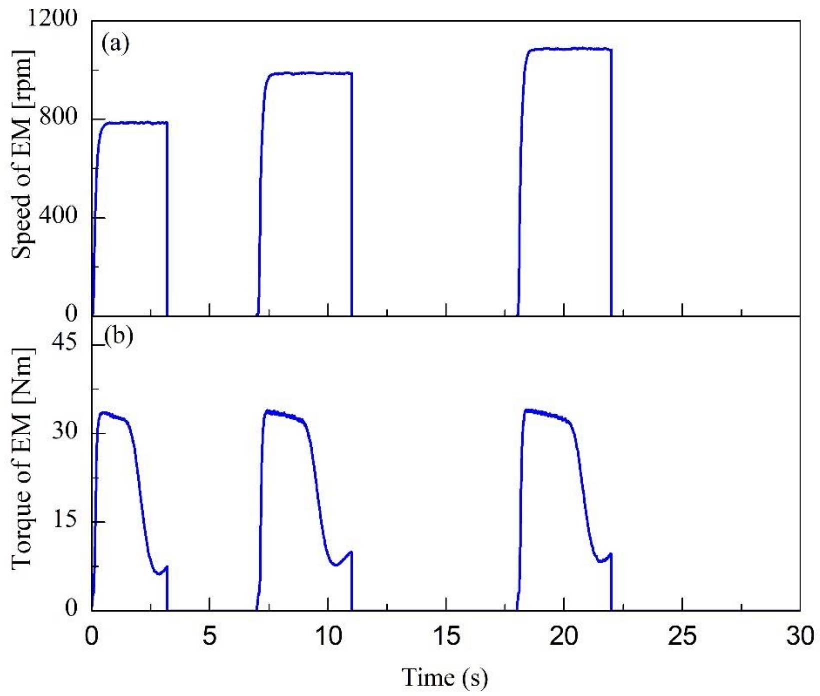

Fig. 5.10 *Experimental results of conventional system (2)*

The electric motor worked from 0 s to 3.2 s in the first cycle in Fig. 5.10. As a comparison, the electric motor of the proposed system worked from 0 s to 2.5 s in proposed system. But the torque of electric motor in stage 2 is larger than that in stage 1 in Fig. 5. 10. Because, the required energy of stage 2 is lower than that of stage 1.

Finally, the energy consumption of the proposed system is reduced. The energy consumption of the conventional system and the proposed system are 25.7 kJ and 19.6 kJ. Hence, the energy saving efficiency of the proposed system is 23.7%

The experiment of high inertia was conducted, and the experiment results are shown in Fig. 5.11 and 5. 12.

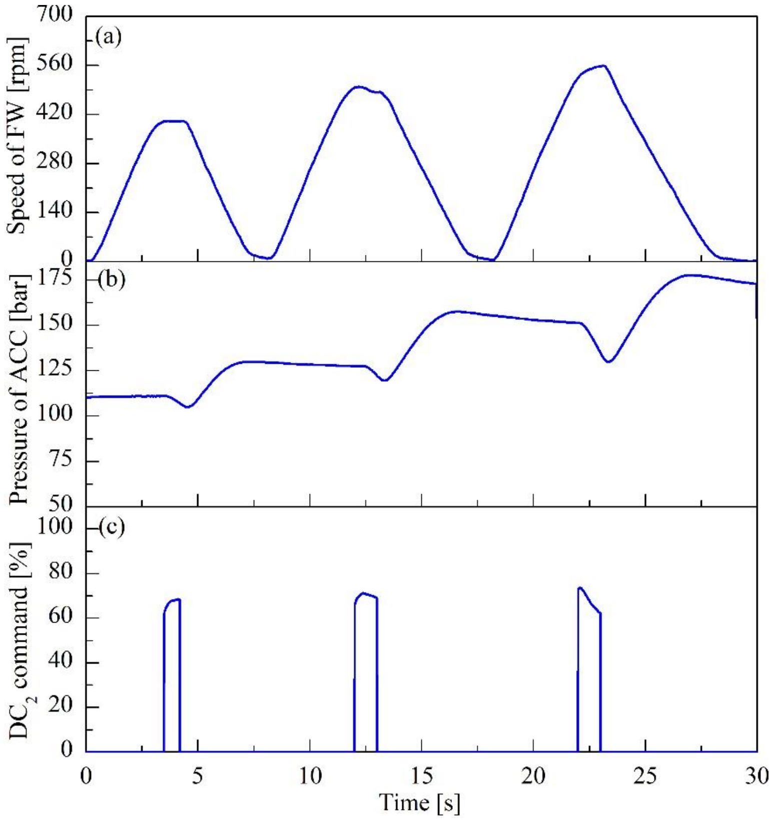

Fig. 5.11 *Experimental results of proposed system (1)*

The kinetic energy of flywheel was regenerated in stage 3 and was reused in stage 2 of each cycle in Fig. 5. 11 and 5. 12. Finally, the energy consumption of the proposed system is 33kJ. The accumulator pressure was 110 bar at beginning, and 170 bar after three cycles of running. Hence, the increased energy of accumulator was 8.6kJ. The estimated energy consumption was 24.4 kJ.

As a comparison, the experiment of conventional system was conducted, and the results are shown in Fig. 5. 13 and Fig. 5. 14. The kinetic energy of flywheel cannot be regenerated. Only the main pump provided energy to drive the flywheel. The energy consumption of the conventional system is 34.7 kJ. Hence, the energy saving efficiency of the proposed system is 29.7% in condition of high inertia.

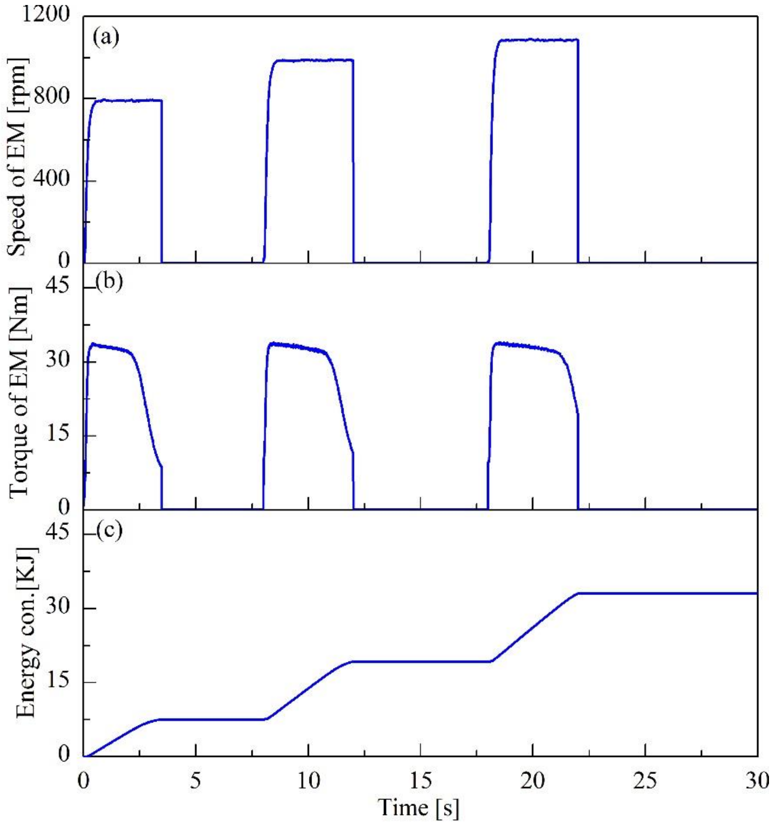

Fig. 5.12 *Experimental results of proposed system (2)*

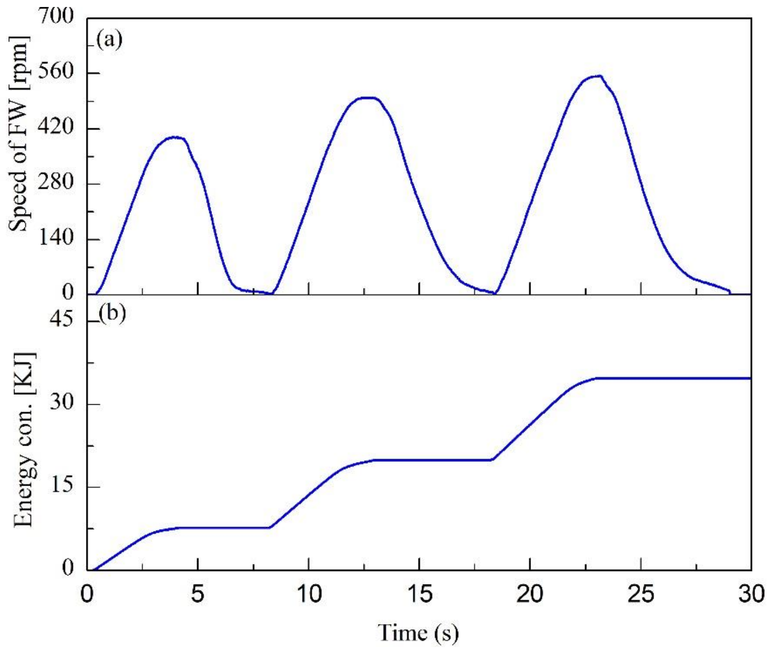

Fig. 5.13 *Experimental results of conventional system (1)*

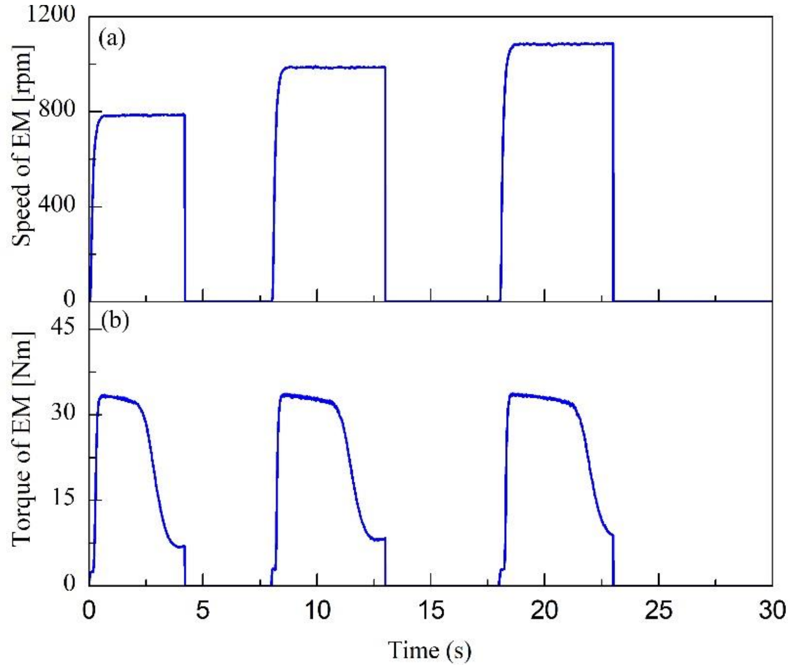

Fig. 5.14 *Experimental results of conventional system (2)*

The energy saving efficiencies of the proposed system are 23.7% and 29.7% in condition of low inertia and high inertia respectively. The average energy saving efficiency is 26.7%.

5.5 Chapter summary

In this chapter, the experiment on test bench was carried out in three steps:

Firstly, the experiment was done with CCHF control strategy. As a conversion, another experiment was done with the constant FCV control strategy. The regenerated energy is improved 64%, and the fluctuation of the flywheel speed was decreased by using the CCHF.

Secondly, the variable accumulator control strategy was utilized in the system experiment. The regenerated energy was tested in different conditions. Finally, the improvement ratio of the regeneration energy was from 2% to 27%.

Thirdly, the energy regeneration efficiency in different conditions are tested. The system can regenerate much energy in different initial flywheel speed, accumulator pressure, deceleration time and inertia. The energy regeneration efficiency is 23% to 51%. The experiment results are also analyzed to show each factor's affection of energy regeneration efficiency.

Finally, the energy saving efficiency was tested by experiment. Both energy regeneration and energy reuse are teste in multiple cycles of working. The average energy saving efficiency is 26.7%.

Chapter 6. CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

This thesis presents a novel energy saving swing system of excavator. The control strategy of energy regeneration mode and energy reuse mode are proposed. The experiments were done to test the energy regeneration efficiency and energy reuse efficiency.

Firstly, the current researches of energy saving of hydraulic excavator is discussed. The electric hybrid excavator and hydraulic hybrid excavator are analyzed. The current control strategies are presented.

Secondly, the hydraulic hybrid swing system in proposed. In this system, the kinetic energy can be regenerated during deceleration of swing part. The variable hydraulic motor is utilized in the system to improve the system performance. The FCV is installed in the system to regulate the flow rate through the hydraulic accumulator. Two independent hydraulic accumulators are used in system as the ESU. The system can also reuse the regenerated energy to reduce the total energy consumption.

Moreover, the novel control strategy is proposed to improve the energy regeneration efficiency. The CCHF control strategy and variable accumulator control strategy are presented. The HMD and FCV can be controlled together to improve the energy regeneration efficiency. The variable accumulator control strategy improves the regenerated energy in case of low accumulator pressure. Then, the control strategy of energy reuse is designed. The stored energy is reused in the stage 2 of one working cycle to reduce the energy consumption of the hydraulic pump.

Next, the experiment was done to test the proposed control system on the proposed system. The regenerated energy can be improved 64% by using the CCHF control strategy. The fluctuation of the swing part is also improved. The improvement ratio of energy regeneration efficiency is 2%

to 27% with the variable accumulator control strategy. The energy regeneration efficiency is from 23% to 51%, based on the experiments in different conditions. The experiments of multiple cycles are conducted. The average energy saving efficiency is 26.7%.

The system could reduce the energy consumption, which is proved by the experiment results. The hydraulic hybrid technology is applied in the proposed system with several additional hydraulic components. These additional hydraulic components are all commercial products with low cost. Hence, this proposed system is easy to be utilized in the real hydraulic excavator with low cost and high energy saving efficiency.

6.2 Future works

The further works may need to include the following two aspects:

- In this thesis, the energy saving efficiency does not get the highest value. Optimization of the control strategy to improvement the energy reuse efficiency and energy saving efficiency can be researched in the future.
- The experiment is done in the test bench. But the test bench has limitation, such as the flywheel speed. In the future, the research of real excavator swing system is necessary.

LIST OF PUBLICATIONS

A. International Journals:

[1] **Ying-Xiao Yu** and Kyoung Kwan Ahn, Optimization of energy regeneration of hybrid hydraulic excavator boom system, Energy Conversion and Management, Vol. 183, pp. 26-34, 2019.

[2] **Ying-Xiao Yu** and Kyoung Kwan Ahn, Energy Regeneration and Reuse of Excavator Swing System with Hydraulic Accumulator, International journal of precision engineering and manufacturing – green technology, https://doi.org/10.1007/s40684-019-00157-7.

[3] **Ying-Xiao Yu** and Kyoung Kwan Ahn, Improvement of Energy Regeneration for Hydraulic Excavator Swing System, International journal of precision engineering and manufacturing green technology, https://doi.org/10.1007/s40684-019-00165-7.

B. Domestic Journals:

[1] **Ying-Xiao Yu**, Eunjin Jeong and Kyoung Kwan Ahn, Review of Energy Saving Technology of Hybrid Construction Machine, Journal of Drive and Control, Vol.15 No.4 pp.91-100, 2018.

[2] Tri Dung Dang, Hoai Vu Anh Truong, Cong Minh Ho, Hoang Vu Dao, **YU YINGXIAO**, Eunjin Jeong and KyoungKwan AHN, Design, Modeling and Analysis of a PEM Fuel Cell Excavator with Supercapacitor/Battery Hybrid Power Source, Journal of Drive and Control, Vol. 16 No. 1 pp. 45-53.

C. Conference:

[1] **Ying-Xiao Yu**, Debdatta Das, Truong B. N. M and Kyoung Kwan Ahn, A Study on the Energy System of Boom for Hybrid Hydraulic Excavator, 15th International Conference on Control, Automation and System (ICCAS 2015), Oct. 13-16, 2015, Busan, Korea.

[2] **Ying-Xiao Yu**, Debdatta Das, Minh-Truong Ngoc Bui and Kyoung Kwan Ahn, Study on Energy Regeneration for Boom System of Hybrid Hydraulic Excavator, The 19th International Conference on Mechatronics Technology (ICMT2015), Nov. 27-30, 2015, Tokyo, japan.

[3] **Ying-Xiao Yu** and Kyoung Kwan Ahn, Study on the Energy Regeneration of Hybrid Hydraulic Excavator using Hydraulic Transformer, 16th International Conference on Control, Automation and System (ICCAS 2016), Oct. 16-19, 2016, Busan, Korea.

[4] **Ying-Xiao Yu** and Kyoung Kwan Ahn, Application of Hydraulic Transformer on Energy Saving for Boom System of Hybrid Hydraulic Excavator, The 20th International Conference on Mechatronics Technology (ICMT2016), Oct. 28-31, 2016, Dalian, China.

[5] **Ying-Xiao Yu** and Kyoung Kwan Ahn, Application of Hydraulic Transformer on Energy Saving for Boom System of Hybrid Hydraulic Excavator, The 9th International Conference on Fluid Power Transmission and Control (ICFP 2017), Apr. 11-13, 2017, Hangzhou, China.

[6] **Ying-Xiao Yu**, and Kyoung Kwan Ahn, Study on Novel Structure and Control of Energy Saving of Hydraulic Hybrid Excavator, 17th International Conference on Control, Automation and System (ICCAS 2017), Oct. 18-21, 2017, Jeju, Korea.

[7] **Ying-Xiao Yu**, Kyoung Kwan Ahn, Hyung gyu PARK, Yang Hun IM and Bo Moon SEO, A Novel Hybrid Sing System and Energy Regeneration Time Control, 10th JFPS International Symposium on Fluid Power, Automation and System, Oct. 24-27, 2017, FUKUOKA, Japan.

[8] **Ying-Xiao Yu**, Eunjin Jeong and Kyoung Kwan Ahn, Research on Energy Regeneration of a Hydraulic Excavator Boom System, 2018 Spring Conference on Drive and Control, Jun 2018, Korea.

[9] **Ying-Xiao Yu**, and Kyoung Kwan Ahn, Research on Energy Saving of an Electric Forklift system, 22th International Conference on Mechatronics Technology (ICMT2018), Oct. 26-29, 2018, Jeju, Korea.

[10] **Ying-Xiao Yu**, and Kyoung Kwan Ahn, Optimization of Energy Saving and Control Performance in the Hybrid Hydraulic Excavator Boom System, 5th China- Japan joint workshop on Fluid Power, July. 23, 2018, Beijing, China.

[11] **Ying-Xiao Yu**, and Kyoung Kwan Ahn, Energy Saving of an Electric Forklift with Hydraulic Accumulator, 17th International Conference on Control, Automation and System (ICCAS 2019), Oct. 15-18, 2019, Jeju, Korea.

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