공학박사 학위 논문

하이브리드 유압식 굴삭기를 위한 혁신적인 파워트레인 및 고급 에너지 관리 전략

INNOVATIVE POWERTRAIN AND ADVANCED ENERGY MANAGEMENT STRATEGY FOR HYBRID HYDRAULIC EXCAVATOR

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INNOVATIVE POWERTRAIN AND ADVANCED ENERGY MANAGEMENT STRATEGY FOR HYBRID HYDRAULIC 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

DO TRI CUONG

June 2023

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이논문을 공학박사 학위 논문으로 제출함

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Abbreviations

EMSs	Energy management strategies
HE	Hydraulic excavator
ERS	Energy regeneration system
ICE	Internal combustion engine
HHE	Hybrid hydraulic excavator
EHCVP	Electrical hydraulic continually variable powertrain
ESC	Extremum seeking control
EM	Electric motors
ESD	Energy storage device
EHA	Electro-hydraulic actuator
CPR	Common pressure rail
DP	Dynamic programming
ECU	Engine control unit
IPC	Industrial personal computer
CVT	Continuously variable transmission
IMV	Independent metering valve

ABSTRACT

Nowadays, along with the development of industry, the demand for fossil fuels is constantly increasing. Therefore, reducing fossil fuel consumption is one of the most important issues worldwide. This aim has opened up opportunities for the development of new low-emission and energy-efficient vehicles. These include hydraulic excavators (HE) which consume a lot of energy and emit a large amount of harmful emissions. To address this challenge, there are two main directions: reducing energy consumption and/or improving energy recuperation capability in HE. Hybrid powertrain combining an internal combustion engine (ICE) with an electric motor is considered an ideal candidate to reduce energy consumption in HE. Meanwhile, an energy regeneration system (ERS) can be integrated into the HE to recover the potential energy and reuse it in subsequent cycles.

Based on the above reasons, an innovative electric hybrid HE named electrical hydraulic continually variable powertrain (EHCVP) which could not only regenerate but also reuse the recovered energy is proposed. In detail, the powertrain includes an ICE and electric motor/generator to drive the main pump. The electric motor/generator can work as a motor or a generator to provide mechanical energy or generate electric energy. The speeds of ICE and motor/generator decide the speed of main pump through planetary gear. Then the ICE's speed can be controlled to the high-efficiency range by changing the operation mode of the electric motor/generator. A variable displacement pump is installed in system to govern the torque of the engine. Hence, the engine working points can be controlled in the high-efficiency range. Besides, a hydraulic motor is placed at the output port of the boom cylinder. The potential hydraulic energy in the boom cylinder is converted into mechanical energy and drives the electric motor/generator via a function of a double clutch without an additional generator. The generated energy from the motor/generator is stored in a battery and it can be reused in subsequent cycles. However, the maximum displacement of the hydraulic pump limits the controlled range of engine torque in a condition of a large velocity. Hence, the current structure of EHCVP limits the improvement of the energy-saving efficiency in the condition of a large velocity. Finally, the fuel consumption of the total system cannot be improved with varying velocities in real engineering.

To enhance energy-saving efficiency, a double clutch with two different gear ratios is installed between the ring gear shaft and hydraulic pump. The ICE's torque can be governed by both the hydraulic pump and gearbox mainly. Meanwhile, the electric motor/generator governs the speed of the engine. In the condition of a large velocity, the bigger gear ratio is used to decrease the speed and increase the torque of the ICE. So, the ICE can work with its high efficiency in the condition of a large velocity.

Compared with the EHCVP without integrating the double clutch, the proposed system could offer improvements in energy saving up to 7%.

For developing a new HE with highly efficient and stability, not only a new powertrain but also an energy management strategy should be proposed. In this thesis, an online energy management strategy based on the extremum seeking control (ESC) is used to switch the gear ratio and efficiently distribute the power to the EHCVP. In addition, the conventional penalty function is caused by suddenly changing the power engine and making the unstable of powertrain when the considered parameter such as SOC of battery beyond the allowable range is replaced by a fuzzy logic system. In detail, the fuzzy logic system is constructed based on considering the battery aging with its input parameters are the current, SOC, and temperature of the battery. During the operation, the fuzzy logic system estimates the output penalty value adjusting the power reference of each power source depending on the battery status.

To verify the effectiveness of the proposed system, a co-simulation model using Matlab and AMESim has been built with a battery model developed in Matlab, and the powertrain and hydraulic circuit were constructed in AMESim to mimic the motion of the HE. Both simulation and experimental results demonstrated that the working points of the engine could be kept within its high-efficiency region under different working conditions.

Chapter 1
INTRODUCTION

1.1. Overview

Nowadays, the energy crisis has been being a very urgent issue. Fossil fuel is gradually exhausted due to the great demand of humans. Specifically, in 2017, it increased by nearly 1.5 times compared to 1990 and reached nearly 10 million kilotons of oil equivalent (KTOE) each year as shown in Fig. 1-1 [1]. It has been reported that coal and oil products accounted for an average of 50% of the world's energy resources and the demand is still increasing. The rise of transport and construction vehicles is undoubtedly one of the most important contributors to this situation [2-8]. In addition, according to research by the energy research organization, most of the CO2 emissions come from coal and oil. The global CO_2 emissions in 2017 also increased 1.5 times compared to 1990 and the number increased steadily over the years as shown in Fig. 1-2 [9]. The huge emissions make the environment worse and adversely affect human health. Therefore, reducing fossil fuel consumption is one of the top priority issues all over the world. These, subsequently, have paved opportunities to develop new environmental and low-emission vehicles, especially hydraulic excavators (HEs) which are commonly used in many fields, but consume a lot of fuel and release large amounts of toxic emissions.

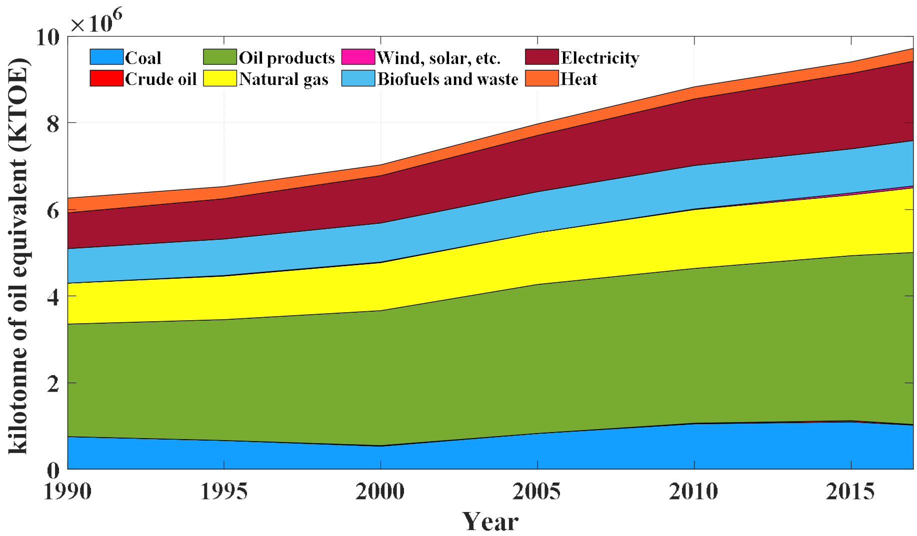


Fig. 1-1 Total final consumption by source, World 1990-2017 (Source: IEA World Energy Statistic and Balances https://www.iea.org/data-and-statistics. [1]).

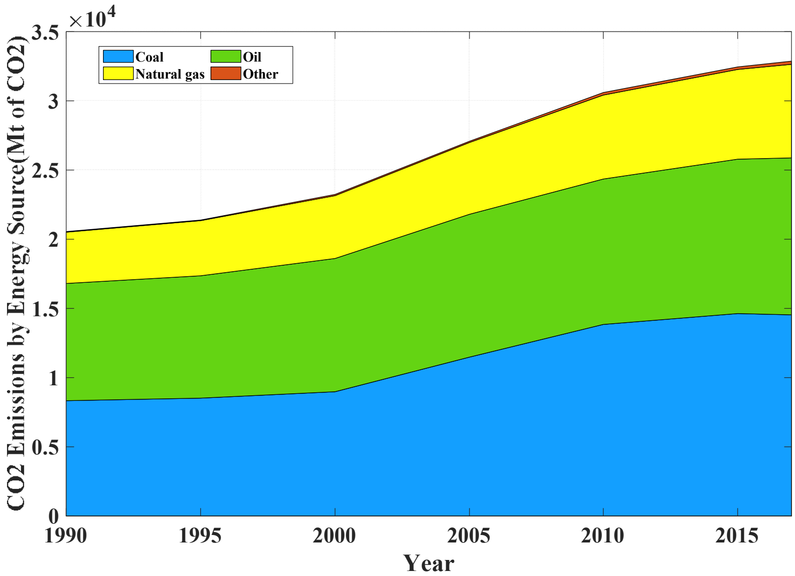


Fig. 1-2 CO2 emissions by energy source, World 1990-2017 (Source: IEA World Energy Statistic and Balances https://www.iea.org/data-and-statistics. [9])

1.1.1. Structure of hybrid hydraulic excavator

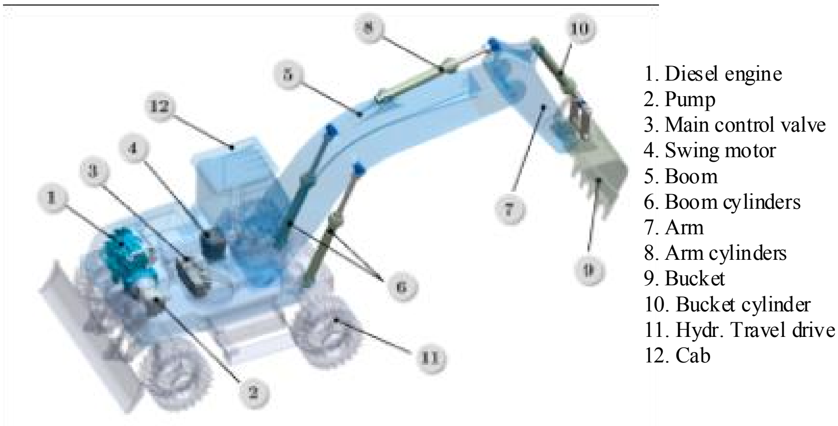


Fig. 1-3 Layout of a typical hydraulic excavator [10]

The overall structure of a conventional HE is depicted in Fig. 1-3 often likens the movements of the working equipment to those of an actual arm. The boom portion of the equipment acts very much like the upper portion of a human arm, including the elbow and the shoulder. The arm portion behaves much like the portion of an arm that starts at the elbow and ends at the wrist. The bucket portion can be compared to a cupped hand. Hydraulic excavators offer much versatility. The buckets in these excavators can be removed and replaced with drills, scissors, or even crushing equipment. It is this level of versatility that makes hydraulic excavators so helpful in a large range of applications. Though the working equipment arm does the digging work, it is not at all the only important part of a hydraulic excavator. The upper structure of an excavator is important as well and can be viewed as the heart of the machine. It holds the engine, hydraulic pump and tank, and swing motors. These important devices are responsible for making the excavator dig and load. The lower section of a HE consists of the mechanisms that make the excavator move along the road, up a hill, or across a construction site. Most hydraulic excavators have crawlers, as they are better suited to moving along rough roads and maneuvering along steep slopes. Crawlers are belt-like tracks used in place of wheels. Hydraulic excavators with crawlers are also more practical for muddy areas than those with wheels.

In the conventional HE, the main pump is directly driven by an ICE which leads to high energy consumption due to changing speed of the ICE during the operation. Therefore, hybrid HE (HHE) and electric HE have been widely considered promising solutions to overcome the energy consumption problem of conventional HE. In the electric HE, the ICE is replaced by an electric motor which is powered by batteries or supercapacitors. Because of the high efficiency and low energy losses of the electric motor, energy consumption can be reduced by about 65% [1]. However, the problem of electric HE is facing that the size is limited due to the battery technology and expensive. Hence, HHE is still an irreplaceable technology today. In HHEs, an ICE is combined with an electric motor/generator to supply power to the system. The ICE still works as the main power source while the electric motor/generator acts as an auxiliary source. During operation, the operating point of the ICE can be easily maintained in the high-efficiency region regardless of the load by changing the working modes of the electric motor/generator. Therefore, HHEs can reduce energy consumption and store excess energy in the battery. Besides, in the HHEs, there are some places where the energy can be captured such as in the boom cylinder during the down movement or flow rate of the swing system during the deceleration process. If it is possible to capture these energies, not only improving the fuel saving but also the working performance of the HHEs can be achieved.

1.1.2. Potential energies

The characteristic of a HE is that it operates a lot of movements during the working motion such as braking, digging, lifting, gripping, swinging, and moving to a new position [11-14]. These operations are performed by the association of the boom, arm, bucket cylinders, and swing hydraulic motor. However, not all movements need to provide power from the main pump, some of which can come to the required position by gravitational force, and the excess energy is largely consumed at the control valve and produces heat which reduces the life of equipment in the system. In the previous research [15, 16], the pressure and flow rate of each part in a 20-t HE are experienced as shown in Table 1-1. The potential energy that the boom cylinder can be generated is 51% and the swing motor is 25% of the total recoverable energy in the excavator. They are two parts that able to generate big potential energy and contribute to all the actions. However, the energies in these actuators are changed according to the weight of the load and the distance of the cylinder or the rotation angle of the swing motor as shown in Fig. 1-4 and Fig. 1-5. Typically, they will be converted into different forms of energy depending on the energy storage device of the ERS. Hence, the development of a suitable configuration can increase energy regeneration and fuel saving.

Table 1-1 Potential energies in HE. [15, 16] Copyright 2017. Elsevier

Actuators	Regenerated energy (J)	Proportion (%)
Boom	132,809	51
Arm	28,456	11
Bucket	34,704	13
Swing	66,472	25

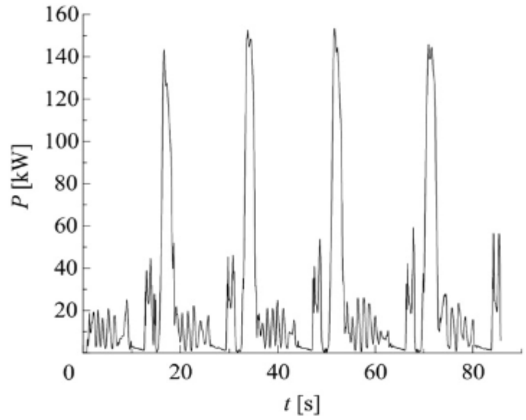


Fig. 1-4 Power requirement of HE in digging condition. [16]

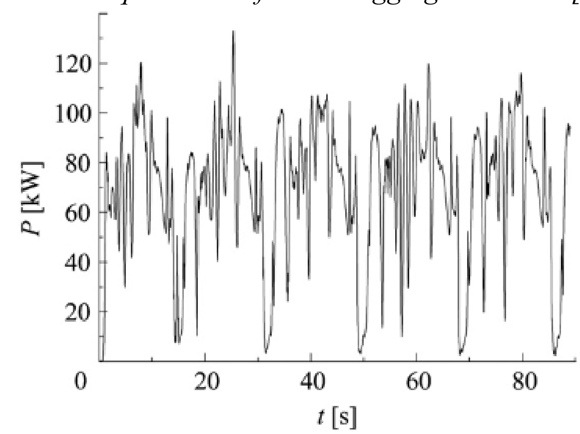


Fig. 1-5 Recoverable energy of the boom cylinder in digging condition. [16]

1.1.3. Drawback of previous research

Hybrid hydraulic excavators (HHEs) have been widely considered one of the most promising solutions to overcome the energy consumption problem of conventional HE [17]. In HHEs, an internal combustion engine (ICE) is combined with an electric motor/generator to supply power to the system. The ICE still works as the main power source while the electric motor/generator acts as an auxiliary source. During operation, the operating point of the ICE can be easily maintained in the high-efficiency region regardless of the load by changing the working modes of the electric motor/generator. Therefore, HHEs can reduce energy consumption and store excess energy in the battery. The configuration of the HHEs has been developed with several concepts such as series, parallel, and compound [2]. In the series HHE architecture, the power from the ICE is converted to electric energy through a generator. During the operation, this electric energy is converted again into mechanical power and supplied to electric motors. In 2007, Kobelco released a commercial 6-ton class HHE using the series powertrain in which the ICE is directly connected to a generator [18]. The energy consumption could be reduced by 40% or more compared with conventional HE. To improve the fuel economy of the conventional serial HHE, Wang et al. proposed a new series hybrid configuration based on electro-hydraulic composite energy storage [19]. In this system, an accumulator was used to capture the potential energy from the actuators. Then, the stored energy could be converted to electric energy through an electric motor/generator, and a hydraulic pump/motor and supply to the electric machines. During the operation, the ICE provided the average power and the excess part was supplied by the battery and accumulator. Simulation and experiment results based on a 7-ton crawler excavator configuration indicated that the variation range of SOC battery was limited from 40% to 60%. The energy-saving of the system could achieve 33%. New Holland Construction presented a hybrid 7-ton parallel hydraulic excavator at the 2006 Internet show [20]. According to the report from New Holland, both fuel consumption and CO2 emission were reduced by 40%. In 2008, Komatsu released a full-scale HHE PC200-8 integrated compound powertrain [21]. The fuel consumption of PC200-8 could be reduced by 7% compared with the conventional excavator. To evaluate the advantages and disadvantages of the three configurations, Kwon et al. [22] made a comprehensive comparison based on fuel consumption, installation cost, and the expected payback time. The authors indicated that the serial configuration could achieve the lowest fuel consumption but the highest additional cost. The parallel configuration had high fuel consumption, however, the lowest additional cost. According to the comparison result, the compound type is a good solution for short-expected payback time and high-reliability purposes.

In HE, there are some places where the energy can be captured such as in the boom cylinder during the down movement or flow rate of the swing system during the deceleration process [23-25]. In fact, potential energy in boom cylinders accounts for 51% of the total recoverable energy. Therefore, most energy regeneration systems (ERSs) are developed to recover the boom energy [17]. ERSs can be categorized into two main types: hydraulic and electric according to the energy storage devices. Hydraulic ERSs use a hydraulic accumulator to store energy as well as absorb shock pressure and maintain the standby of the power source. Ge et al. [26] presented a gravitational potential energy recovery system using an accumulator and a conversion cylinder. During the operation, the hydraulic power in the conversion cylinder was directly stored and reused in the accumulator without increasing the cost and installed power. The simulation results indicated that the system could recover 75.9% of the gravitational potential energy in the lowering process and reduced energy consumption by 41.8%. Chen et al. [27] proposed a new ERS based on a closed-circuit hydrostatic transmission that adopted a hydraulic accumulator as the main energy storage element to overcome the problems of high throttling loss of the open circuit. In detail, the state of the boom cylinder was directly controlled by the rotation direction of hydraulic pumps/motors and the entire gravitational energy was stored in the accumulator.

Experiment results showed that energy regeneration efficiency can achieve from 60% to 68.2% according to different working conditions. Although hydraulic ERSs offer a lot of advantages such as high energy regeneration efficiency, emergency backup, vibration, and shock reduction, the main drawback of hydraulic ERSs is that they require the use of throttle valves or hydraulic transformers to guarantee safety and stability. Besides, energy regeneration efficiency is also affected by the pressure in the accumulator. The authors therefore must correctly calculate and select the initial pressure of the accumulator to achieve the highest efficiency.

In contrast to the hydraulic ERS, electric ERSs can overcome the problems of installation spaces, limited capacity, and initial setting parameters by using a battery/supercapacitor to store the recovered energy. Yu et al. [28] placed a hydraulic motor at the outlet port of the bore chamber to reduce energy losses. In addition, a flow control valve was integrated to regulate the flow rate through the hydraulic motor. Hence, the hydraulic motor's working point was maintained in a high-efficiency area. Experiment results showed that the energy regeneration efficiency can achieve 57,4%. Considering the sizing of energy regeneration devices and cylinder velocity fluctuation of the conventional electric ERS, some authors [29-31] proposed a new electric ERS structure that could take advantage of both hydraulic accumulators and batteries. When the cylinder moved down, the energy in the bore chamber quickly charged and increased the pressure in the accumulator. After reaching the set pressure threshold, the accumulator discharged the pressurized flow rate and combined it with the power from the boom cylinder to drive a hydraulic motor and a generator. Consequently, the hydraulic power was converted to electric power and stored in the battery. With the proposed system, the fluctuation of the boom cylinder was reduced, and the rotational time of the generator could be increased. The experiment results showed that an estimated 39% of the total recoverable boom energy could be captured while the regeneration efficiency of the conventional ERS was approximately 36%. The rated power of the electric generator was also decreased by more than 65%. In particular, the electric ERS is especially suitable for integration in hybrid HE where the powertrain already has an electric motor. With this configuration, the stored energy in the battery can be easily reused by the electric motor during operation.

For developing a new HE with highly efficient and stability, not only a new powertrain but also an energy management strategy should be proposed. Wang et al. applied dynamic programming (DP) to obtain the optimal working state of the series powertrain based on the load spectrum curve of the real HE to reduce energy consumption. Chen et al. presented an EMS-based genetic algorithm to optimize the power of ICE based on fuel-rate, battery SOC, and driveline power demand [27]. Roland discussed the trade-off between the optimality and computational efficiency of a parallel powertrain with the use of EMS-based Pontryagin's Minimums Principle (PMP) [32]. However, in order to derive an optimal power distribution for the hybrid powertrain, these methods need to solve their optimization problems offline with the need for prior knowledge of the drive cycle.

On the other hand, concerning the complexity of the HE, it might be impossible to capture its dynamics just by mathematical modeling, which is required by various energy management schemes. Hence, a model-free, real-time energy management strategy would be a more suitable candidate for the HE. Teodorescu et al. applied the ECMS for a parallel hybrid forklift to minimize fuel consumption and maintain the state of charge (SOC) of the supercapacitor in the optimal range by changing the engine speed corresponding to the load condition [33]. Anders et al. used the ECMS for a parallel powertrain HE with considering the power consumption of the ICE, and the inner and kinetic power of the electric motor in a Hamiltonian function [34]. By minimizing this function, the optimal fuel control of the ICE could be estimated, and the dynamics of the powertrain became smoother. Yu et al. developed a real-time EMS based on DP-extremum seeking (ES) [35]. In which, DP was used to ensure the approximate global energy optimality and SOC sustainability, while ES compensated the control signal from the DP to reduce fuel consumption in real-time operation. However, these studies have just focused on maximizing the ICE efficiency and reducing energy consumption without consideration battery aging.

1.2. Research objectives

From the above analysis, it is clear that both hybrid powertrain and energy regeneration systems play an important role in reducing energy consumption and emissions in the HEs. However, the hybrid/electric ERSs have just focused on energy regeneration efficiency and studied independently with the hybrid powertrain without mention of how to reuse the recovered energy. Even if the energy regeneration efficiency is high, fuel consumption cannot be reduced without reasonable structure and energy management strategy in energy reuse mode.

Based on these reasons, this thesis proposed an innovative powertrain named electrical hydraulic continually variable powertrain (EHCVP) which an ICE and an electric motor/generator are used to provide the power for the boom system. During the operation, the torque and speed of the ICE can be adjusted to shift its working point into its optimal working region by using the double clutch with two different gear ratios. Besides, a hydraulic motor is placed at the output port of the boom cylinder. The potential hydraulic energy in the boom cylinder is converted into mechanical energy and drives the electric motor/generator via a function of a double clutch without an additional generator. The generated energy from the motor/generator is stored in a battery and it can be reused in subsequent cycles.

In addition, an online energy management strategy based on the extremum seeking control (ESC) is used to switch the gear ratio and efficiently distribute the power to the EHCVP. In addition, the conventional penalty function caused by suddenly changing of the power engine and making the unstable of powertrain when the considered parameter such as SOC of battery beyond the allowable range is replaced by a fuzzy logic system. In detail, the fuzzy logic system is constructed based on considering the battery aging with its input parameters are the current, SOC, and temperature of the battery. During the operation, the fuzzy logic system estimates the output penalty value adjusting the power reference of each power source depending on the battery status.

To verify the effectiveness of the proposed system, a co-simulation model using Matlab and AMESim has been built with a battery model developed in Matlab, and the powertrain and hydraulic circuit were constructed in AMESim to mimic the motion of the HE. Both simulation and experimental results demonstrated that the working points of the engine could be kept within its high-efficiency region under different working conditions.

1.3. Limitations

In this work, an innovative powertrain named EHCVP managed by an advanced energy management strategy was developed for the hybrid hydraulic excavator to optimize energy regeneration and energy-saving capability. The results showed that during operation, the working point of the ICE was kept in its high-efficiency region and the excess energy could be compensated by the electric motor/generator. In addition, the recoverable energy in the boom cylinder can be captured and stored in the battery with the energy regeneration efficiency could be reached to 48.2%. Compared with the conventional EHCVP, the proposed EHCVP can improve energy saving by about 7%. Besides, by using the proposed EMS up to 3.35% of the battery health could be saved, leading to 33% improvement in capacity loss based on 50000 working cycle projections. However, some limitations of the thesis are remaining as follow:

- The torque of the ICE should be adjusted according to different working conditions to achieve optimal efficiency. Therefore, a continuously variable transmission (CVT) should be used to adaptively adjust the gear ratio related to the load of the boom cylinder to enhance the efficiency of ICE.
- In addition, a learning-based method should be combined with the ESC to not only adaptively adjust the transmission ratio of CVT but also enhance the working performance of the battery.

1.4. Thesis outline

The research outline of this dissertation is arranged as follows:

- Chapter 1 introduces the motivations, research objectives, limitations, and outlines of this thesis.
- Chapter 2 presents the developments of the hybrid powertrains and energy regeneration systems in HHE.
- Chapter 3 describes the structure of the proposed powertrain.

- Chapter 4 reports an improvement in energy saving for HHE using a double clutch.
- Chapter 5 presents an advanced energy management strategy based on fuzzy extremum-seeking methods.
- Chapter 6 concludes the thesis and proposes future works.

Chapter 2
DEVELOPMENTS OF HYBRID HYDRAULIC EXCAVATOR (HHE)

2.1. Introduction

To reduce energy consumption and take advantage of these recoverable energy sources, many HHE approaches have been proposed. This chapter, therefore, aims to carry out a comprehensive review of the current state-of-art of hybrid powertrain configuration and energy regeneration technologies in HEs.

2.2. Powertrain configurations of hybrid HE

The conventional powertrain configuration [16] of a typical hybrid HE is depicted in Fig. 2-1. In this configuration, hydraulic pumps are driven by an internal combustion engine (ICE) to power up the actuators such as boom, arm, and bucket cylinders and driving and swing hydraulic motors via hydraulic control valve block.

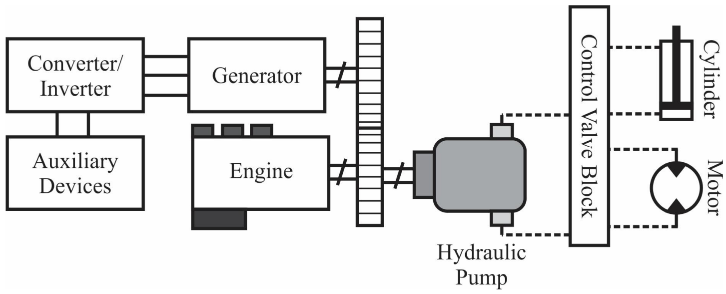


Fig. 2-1 The conventional powertrain configuration on a construction machine

In a conventional hydraulic excavator, the pumps must always supply hydraulic power corresponding to the maximum workload to ensure the required power in all working conditions. Therefore, in low-load working conditions, the excessive power is dissipated as heat. Moreover, the total surplus potential energy generated by lowering the boom and kinetic energy by braking the swing motion is also squandered as heat. For example, as in Fig. 2-2, only 13% of energy is extracted as effective work, and the remainder is generally discarded as heat loss [36]. In addition, in [18] Masayuki K. et al. pointed out that the total efficiency of the conventional hydraulic excavators only achieves 20% as illustrated in Fig. 2-3 due to the loss of power in the hydraulic pump, hydraulic system, and mechanical system. The energy loss and the efficiencies of subsystems leads to the low total energy efficiency of the conventional excavator.

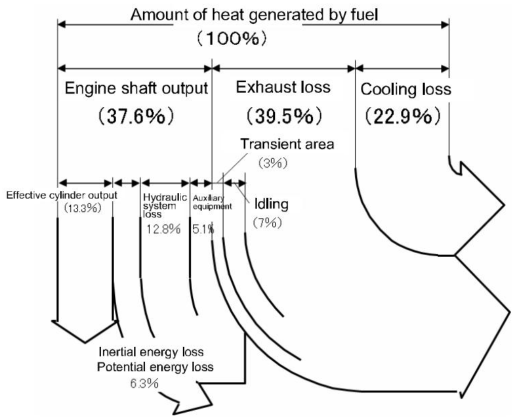


Fig. 2-2 The amount of heat generated by fuel

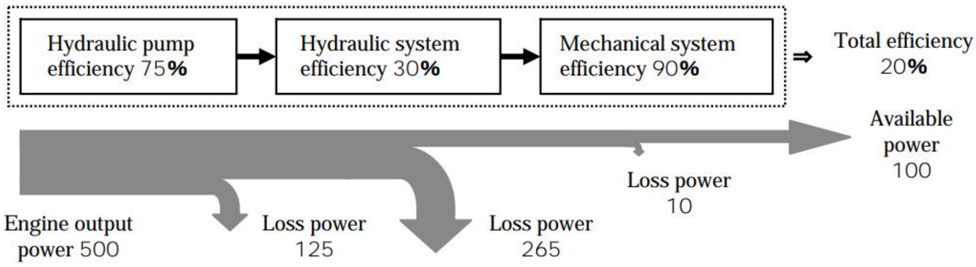


Fig. 2-3 The energy flow in typical work of a hydraulic excavator

Therefore, a question is raised as how to improve the system efficiency of hydraulic excavators in the face of challenges in terms of fossil fuel shortage and environmental pollution due to pollutant emissions. To deal with the above-mentioned problems, many studies have been accomplished [16, 18, 36-41]. The solutions to the efficiency improvement problem focus on the development of new powertrain configurations by combining two or more distinct power sources, so-called hybrid configurations, and the utilization of higher efficient actuators replacing conventional actuators in hydraulic construction machines. The results show that energy consumption is significantly reduced, and efficiency is greatly improved. The hybrid configurations can be divided into two types including engine hybrid and fuel cell hybrid powertrains which are thoroughly discussed in the following sections. To improve the fuel economy and increase the efficiency of construction machines, the engine hybrid configuration was firstly investigated. In this configuration, the main supply power still comes from the ICE engine, however, the size of this engine can be significantly reduced by employing auxiliary power sources that act as storage devices that complement energy in conjunction with the engine when needed. Moreover, the dissipated energy generated in the conventional powertrain configuration will be saved in this storage device, which contributes to considerably improving the fuel consumption of the engine hybrid configuration. Engine hybrid architectures for construction machines can be classified into serial, parallel, and series-parallel (compound) types which will be discussed and analyzed in the following sections.

2.2.1. Series powertrain configuration

The typical series configuration is explicitly depicted in Fig. 2-4. Compared with the conventional powertrain, in this configuration, the total mechanical energy generated from ICE is converted into electric energy by employing a generator. The main part of this energy is utilized to power the electric motors (EMs) which drive hydraulic pumps, whereas the remainder is consumed to charge energy storage devices (ESD) depending on the working condition of the construction machines. To stabilize the electric voltage generated from the generator, a converter is used to convert this AC voltage to DC-controlled output voltage which is changed into AC voltage to power electric motors in the next step.

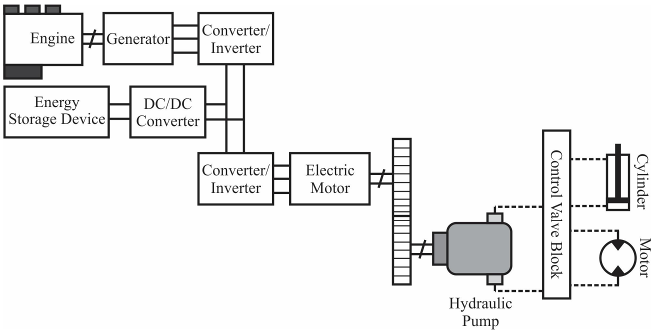


Fig. 2-4 The typical series powertrain configuration on engine hybrid construction machinery

The series powertrain configuration was successfully utilized in wheel loader ZW220HYB-5B [38] by HITACHI CONSTRUCTION MACHINERY CO., LTD in 2003 as shown in Fig. 2-5. In this configuration, the engine drives the generator and the electric power from the generator drives the traction motors. Based on that there is no mechanical power transmission coupling between the engine and axles. The electrical storage devices are connected to DC bus via a DC/DC converter, which is charged during deceleration and discharged during acceleration to return this energy to the traction motor. It allows to reduce the fuel consumption and the emissions are improved.

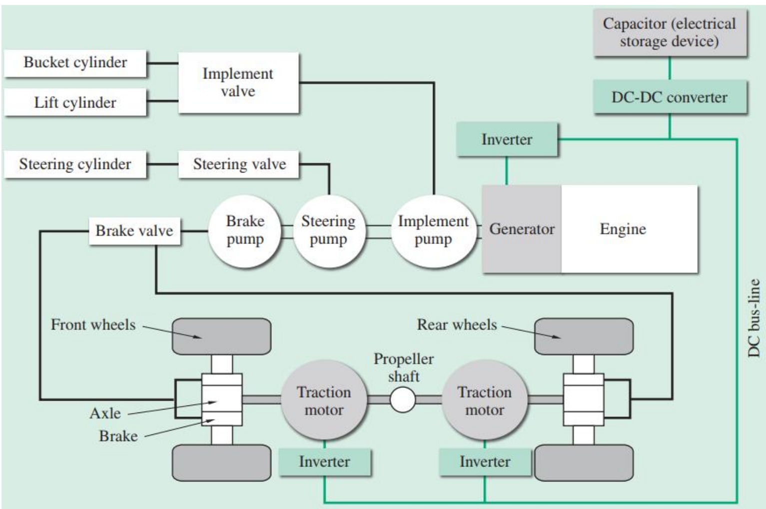


Fig. 2-5 Series powertrain configuration of ZW220HYB-5B wheel loader introduced by Hitachi

The typical series powertrain of a 6-ton class hybrid excavator which is introduced by Kobelco [18] in 2007 is depicted in Fig. 2-6. The swing motion is driven by an EM, whereas the motion of the bucket, arm, and the boom is driven by hydraulic cylinders and the traveling of the excavator is provided by left and right hydraulic motors. The potential/kinetic energy when the boom lowering and during the deceleration of the swing motor is stored in ESS which comprises of battery and supercapacitor. By employing this powertrain configuration, the experiment results showed that the fuel consumption was reduced by more than 60%.

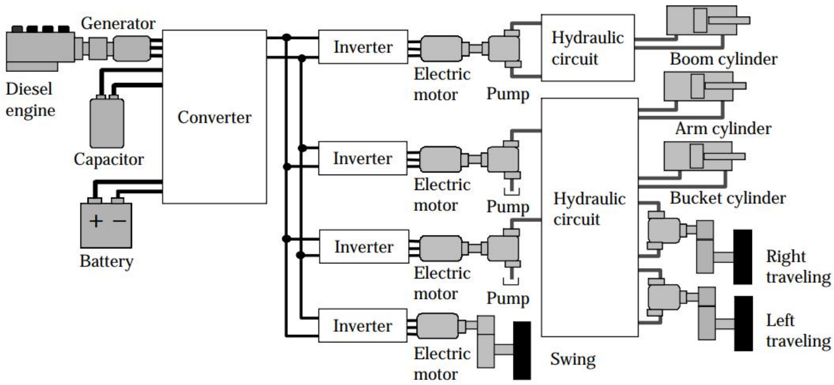


Fig. 2-6 The series powertrain configuration on KOBELCO 6-ton class machines

2.2.2. Parallel powertrain configuration

The typical parallel powertrain configuration in engine hybrid construction machines is illustrated in Fig. 2-7. In this configuration, the hydraulic pump and generator are driven to work by the ICE. The output energy of the ICE is directly supplied to the pump without energy conversion. In the low-load and medium-load working conditions, the total energy is supplied by the ICE, and M/G works in generator mode to charge ESD via DC/DC converter. In the heavy-load condition, the major energy supplied to the hydraulic pump comes from the ICE and the remaining energy is supplied by the EM which consumes the energy stored in the ESD. The most interesting feature of this configuration is that a little change in the powertrain structure of the conventional configuration is required to adopt this configuration. This helps to reduce the initial investment for powertrain development and also takes the advantage of hybrid configuration in fuel cost savings and efficiency improvement.

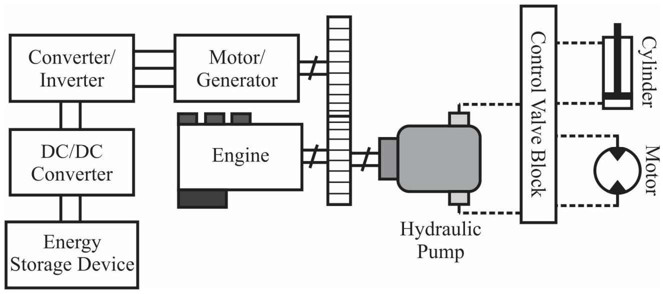


Fig. 2-7 The typical parallel powertrain configuration in construction machines

The parallel power configuration was initially developed on a wheel loader [42] by Hitachi Construction Machinery Co. Ltd in 2003 as illustrated in Fig. 2-8. In this architecture, the engine drives the hydraulic pump and generator in parallel, the pump drives the hydraulic system for working, and the EM drives the wheel movement based on the energy supplied by the generator and/or from the battery.

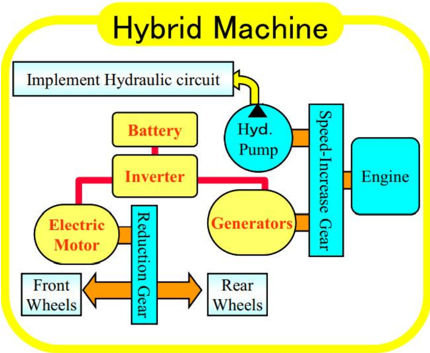


Fig. 2-8 System outline of the HITACHI hybrid wheel loader

2.2.3. Series-parallel powertrain configuration

Taking advantage of both series and parallel types, the compound powertrain configuration is developed. The general series-parallel powertrain configuration is depicted in Fig. 2-9. In this configuration, the generator is directly driven by the ICE engine through a mechanical transmission system. For an engine hybrid excavator, the swing motion is controlled by an EM whose input energy is supplied by a generator and/or ESD depending on the various working conditions such as acceleration or deceleration.

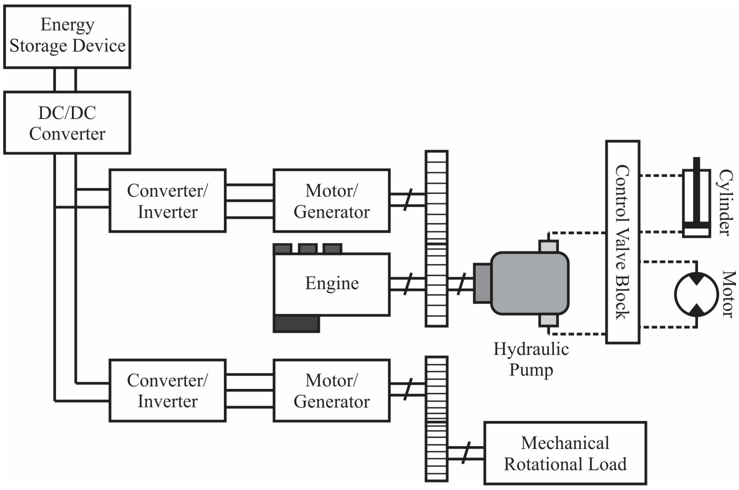


Fig. 2-9 The typical compound powertrain configuration

It can be seen that the compound configuration transformation does not need many changes from the conventional type. Moreover, by employing this configuration, the required rated power of the ICE engine and EM can be relatively small. In addition, the control strategy for this configuration is not too complicated compared with the serial type. Hence, this architecture is the most potential solution for engine hybrid construction machines.

The utilization of compound configuration was developed on 8-ton class hybrid excavator SK80H [40] from Kobelco Construction machinery Co., Ltd in 2013 whose block diagram is shown in Fig. 2-

10. As presented in this architecture, the hydraulic circuits for the boom, arm, bucket, and traveling motors are driven in parallel, whereas the swing motion is driven in series. By using a series-parallel configuration, the required rated power of the engine is reduced significantly from 40kW to 27kW [37]. The ESD adopted to store regenerative energy is a nickel-hydrogen battery whose charging capacity is determined based on the maximum regenerative power of the swing motor. The comparison of the 3 above configurations in presented in Table 2-1.

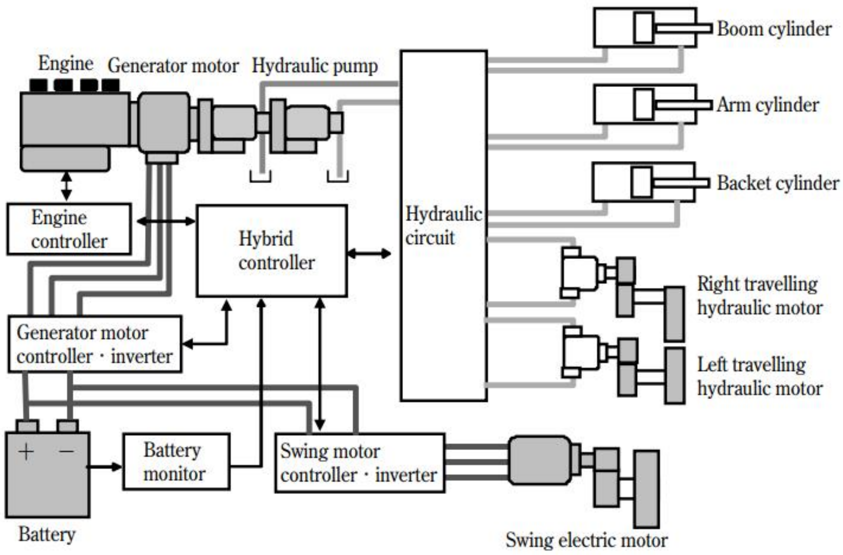


Fig. 2-10 Block diagram of Kobelco 8-ton class series-parallel excavator SK80H

Table 2-1 comparison of 3 above configurations

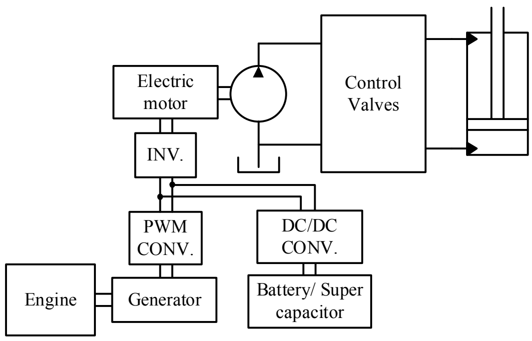
No.	Powertrain configuration	Advantages	Disadvantages
1	Series configuration	- The size of the ICE engine is reduced - High efficiency	- Multiple EMs are used - High cost - Low reliability
2	Parallel configuration	- A small change in the powertrain is required - High transmission efficiency	- Low ICE efficiency - Limited fuel savings
3	Series-parallel configuration	- High ICE efficiency	- Energy management is complex

2.3. Types of Boom, Arm, and Bucket energy regeneration technologies

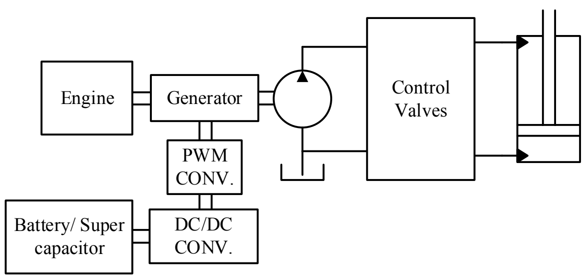
The structure of the 3 parts (boom, arm, bucket) has the same characteristics. They all work based on the extension and retraction of the cylinder. Besides, the potential energy in these components could be recovered by the effects of gravitational force. However, with the boom cylinder, the bore chamber is always a place to store recoverable energy. The ERSs are therefore located at the output port of this chamber. For the arm and bucket cylinders, it is difficult to determine which chamber has recoverable energy during operation. Along with that, the size and the potential energy of the boom cylinder are the largest. Therefore, the researchers only focused on developing ERS for the boom system. In case of necessity, the ERSs for the boom system are completely applicable to the remaining arm and bucket parts with requiring some necessary changes.

2.3.1. ERS using electrical energy storages

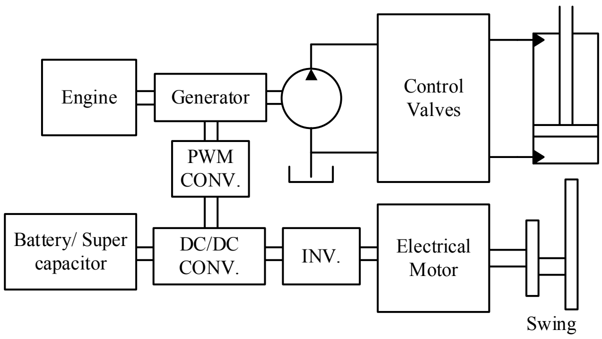
Currently, the power source is one of the deep and extensive research directions on vehicles. In the field of construction machines, manufacturers such as Hyundai, Volvo and CAT tend to replace the internal combustion engine (ICE) with electric motors and storage devices. This has been successfully applied and commercialized in small construction vehicles. However, with large machines working in harsh environments especially big HEs, the current electrical technology has not met the requirements such as durability, large power supply, and sudden changes [43-45]. Therefore, instead of being completely replaced, the ICE is combined with an electric motor to form a hybrid electric power source [5]. In particular, the ICE still plays as the primary energy source for the entire system while the electric motor plays as the secondary source. The use of hybrid power source (ICE and electric motor) offers a high potential in improving ICE efficiency through optimization but also an ability in energy regeneration through the machine operation. Generally, hybrid HE (HHE) can be classified into three main categories based on their architectures, known as series, parallel, and compound. The first configuration of the HHE shown by Kanezawa using the compound configuration [46]. In 2008, Komatsu [21] released a full-scale HHE PC200-8 using the combination of an electric motor and the ICE in the compound category. Kwon et al. [22] made a comparison between various configurations of HE combined with a supercapacitor based on the fuel consumption, the installation cost, and the expected payback time as shown in Fig. 2-11. According to the comparison result, "a compound-type hybrid structure is a better solution than others because of its short-expected payback time and higher reliability" [22]. This study also presented a rule-based power control strategy to manage effectively the power distribution between the engine and supercapacitor according to the load required. The results showed that the proposed control algorithm can obtain the balance of the power requirement and energy consumption. By using the hybrid system and proposed control algorithm, it can be reduced about 24% in fuel consumption compared to conventional HE.



(a)



(b)



(c)

Fig. 2-11 Different structures of HE. (a) Series type. (b) Parallel type. (c) Compound type. [23]

Among three different structures of hybrid power sources, Xiao et al. [47] focused on studying the parallel hybrid type which had the lowest additional cost [22]. The authors developed a control algorithm named dynamic-work-point strategy with two goals. The first one was to ensure the engine operating points within its optimal working region (denoted as the dash area in Fig. 2-12). The second one was to limit the variation of the capacitor SOC. To achieve these goals, the authors utilized a sensitivity value representing the changing threshold of the capacitor SOC. The engine speed was controlled to maintain the capacitor SOC variation between cycles lower than the sensitivity value. However, a valve-controlled system was required in order to compensate any excess power created by the machine when forcing the engine into its optimal operating points whilst limiting the capacitor SOC variation. Consequently, this could cause a waste of power and generated the heat at the main control valve.

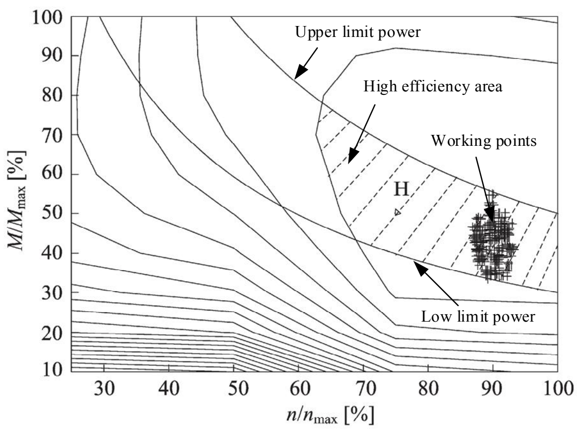


Fig. 2-12 Distribution of engine working points with the hybrid system. [47]

Based on the characteristics of the HHE, the ERS using electric storage devices for boom system also becomes more suitable and has many advantages over other methods. Due to the difference between the potential energy in the boom cylinder and the energy in electric storage devices, electric ERS is forced to use equipment to convert energy from hydraulic energy to electrical energy. Therefore, hydraulic motor and generator are two indispensable devices and are used in all electrical ERSs as presented in Fig. 2-13. During the boom cylinder moves down, flow in the bore chamber will rotate the hydraulic motor and drive the generator. The generated electricity will be stored in the electrical storage device which can be a battery or capacitor and can supply to all actuators at the next cycles.

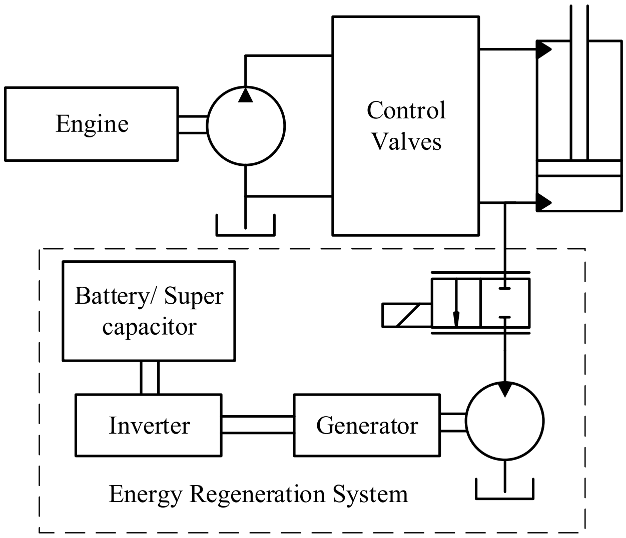


Fig. 2-13 A classical ERS using electrical storage.

According to the classical ERS using the electrical storages, a number of studies have been carried out to improve the system control performance as well as its energy saving ability. Wang et al. [48] proposed a control strategy to enhance the boom performance whilst underpinning the high energy recoverability as shown in Fig. 2-14. Here, characteristics of the classical ERS were modelled by using mathematical equations. Then, a load torque observation was applied to estimate the generator torque and a flow compensation was used to compensate the hydraulic motor leakage. In another study, Wang et al. [49] considered the low dynamic performance of actuators and large capacity of the generator to avoid the overload in conventional ERS. The authors proposed a new ERS that combined regeneration devices (hydraulic motor and generator) and a throttle valve. During the recovery process, the potential energy in boom cylinder was transferred to the hydraulic motor through controlling of the throttle valve. Hence, the regenerative torque was regulated according to the load to avoid the rapid pressure drop through the regeneration system. However, using this valve could lead to increase in the energy loss as well as heat generation.

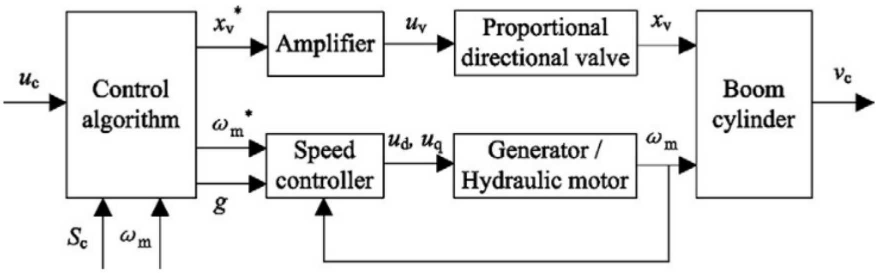


Fig. 2-14 Structure of the energy recovery controller. [25].

To improve the energy efficiency, studies have been focused on how to reduce or eliminate energy losses at main control valves of the conventional hydraulic servo systems. Electro-hydraulic actuator (EHA) system is known as a typical hydraulic system and employed to overcome the problems of the conventional hydraulic systems. In an EHA, states of the cylinder are directly controlled by the rotation of the electric motor without control valves. Therefore, the energy loss in the working process is minimized. Based on this advantage, Yoon et al. [50, 51] proposed a hydraulic boom system using EHA as shown in Fig. 2-15. The EHA system not only worked as the main energy source but also had the ability to recover the energy in boom cylinder. During the moving down process, the main hydraulic pump/motor worked as a motor that drives a generator. The hydraulic energy in the boom cylinder was converted to electric energy and stored in the battery. The effectiveness of the proposed system was verified using a 5-ton class excavator. The results proved that energy saving efficiency could reach up to 54.9%. Bui et al. [52] proposed a new configuration of boom system in which EHA was used as the primary power supply. Knussman et al. [53] utilized a hydraulic pump and an accumulator to act as a source of pressurized oil to integrate into an EHA-based boom system. Other studies on swing systems using EHAs have been also performed. Chowdhury et al. [54] proposed a new swing system using an EHA, and two pairs of hydraulic pump-motor. The maximum energy saving capacity in these cases could be achieved up to 23%. However, the ERSs using EHAs were more expensive than the conventional servo systems due to the sizes and costs of bi-directional pumps and electric servo motors used. Furthermore, except Yoon's system, the other systems required ancillary components to recover and reuse energy. EHAs were also difficult for precise control because of their complex dynamics, high non-linearities and high uncertainties. Another drawback of using EHA is that pressure differences at two ports of the pump when reversing the actuator motion and the low system working frequency (normally up to 5 Hz, compared to 20 Hz of hydraulic servo valves) result in the low dynamic response of the whole system [55, 56]. Therefore, EHAs are generally unsuitable for large size HEs.

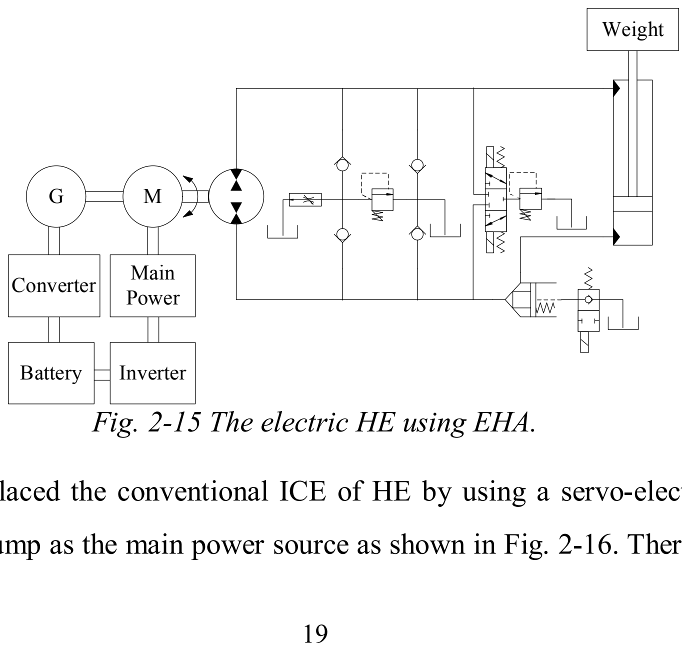


Fig. 2-15 The electric HE using EHA.

Ge et al. [57] replaced the conventional ICE of HE by using a servo-electric motor driving a variable displacement pump as the main power source as shown in Fig. 2-16. Therefore, this HE could guarantee the low emission under variant working operations. In addition, the independent metering valve (IMV) was placed in both two ports of the boom cylinder as depicted in Fig. 2-17 and Fig. 2-18. These valves reduced energy loss and generated heat problems. Moreover, the energy efficiency maps of the main pump and electric motor were estimated following mathematical equations. Based on these maps, a power source efficiency control strategy was proposed. The components in the power source worked in high working efficiency. Then, the system can achieve the demand for high performance, low energy consumption (reduced 65%) and high regeneration efficiency (33% in normal working process and 28.5% in the digging process).

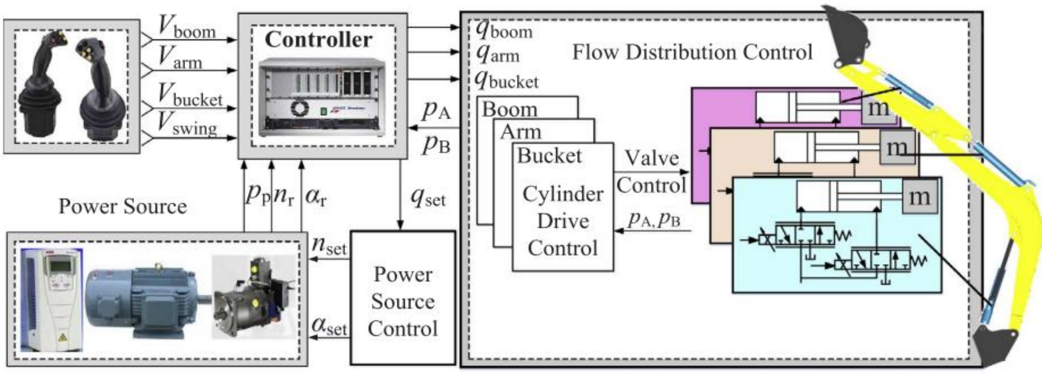


Fig. 2-16 Structure of electric HE using the variable pump and the servo motor. [34].

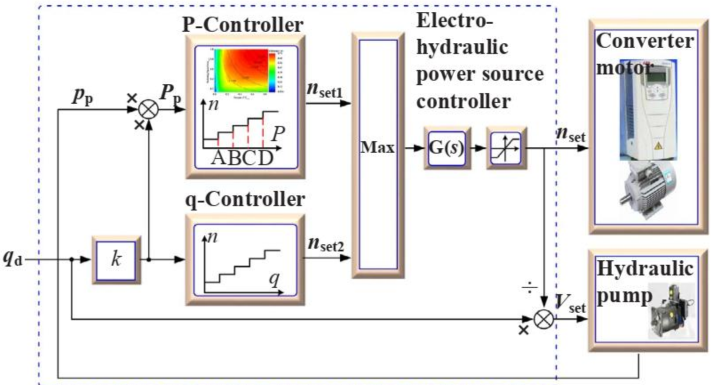


Fig. 2-17 Energy efficiency controller. [34].

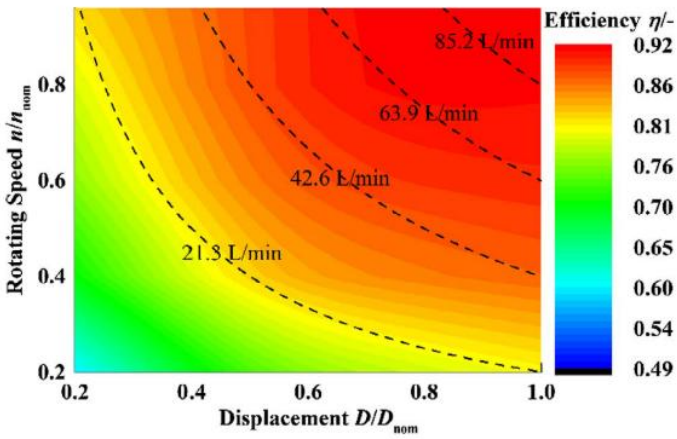


Fig. 2-18 Power source control strategy and efficiency map of the pump. [34]

Considering the conventional ERS, the velocity of the boom cylinder when it moves down is controlled by the rotation speed of the hydraulic motor and the generator. Hence, the working efficiency of regeneration components is changed according to the weight of the load. In the case of a high load and a high speed of the cylinder, the conventional ERS could not keep up due to the limited rotation of the generator. This led to a decrease in the lifetime of the devices as well as the energy that was lost during operation. In addition, the sizes of hydraulic motor and generator should be chosen sufficiently to make sure that the velocity of the boom is not affected. To overcome these problems, Yu et al. [28] used a flow control valve to regulate the flow rate through the variable displacement hydraulic motor. Hence, the torque and speed of the hydraulic motor could be kept in the high working efficiency area with variant operations. Moreover, the regeneration unit was directly placed at the output port of the boom cylinder as shown in Fig. 2-19. Therefore, the proposed system could reduce energy loss at the main control valve. The energy regeneration efficiency could be achieved by up to 57.4%.

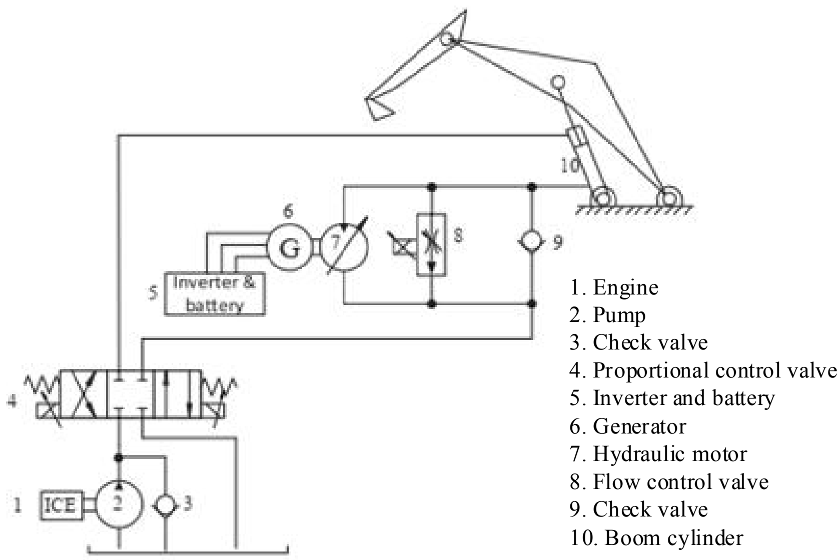


Fig. 2-19 ERS of boom system using an additional flow control valve. [35]

To solve the low-efficiency problem and reduce the size of energy recovery devices in conventional ERS, some authors [29, 30, 58] proposed a novel electric ERS structure that integrated an additional hydraulic accumulator as shown in Fig. 2-20. When the cylinder moves down, the energy is stored directly in the hydraulic accumulator. After the pressure of the hydraulic accumulator reaches the set threshold, the control valve opens. The flow rate from the accumulator and the boom cylinder is supplied to the hydraulic motor driving the generator. This proposed ERS can take advantage of the hydraulic accumulator that it can quickly charge and reduce the flow through the hydraulic motor as well as the speed and torque of the generator. The rated power of the electric generator could be decreased by more than 65% as presented in Fig. 2-21. "The experiment results showed that an estimated 39% of the total potential energy could be regenerated under the standard operating conditions, while the recovery efficiency of the conventional ERS is approximately 36%. In addition, recovery efficiency can be improved under extreme operating conditions” [30].

From the above analysis and a study on ERS using electrical storage, a summary table of development technology is then carried out as shown in Table 2-2. The energy efficiency of electrical ERSs is from 33% to 57%. The power consumption can be reduced by approximately 25%. Besides, the summary table indicated that the merits of these ERSs using electrical storage are that energy recovery processes do not affect cylinder movement [28, 29, 49, 57]. Stored energy in electrical storage can be easily used directly to other devices in the system. However, the demerits of the electrical ERSs are their high energy loss due to converting energy, require complex control strategies and only suitable for small and medium sized HEs [22, 46, 47, 50, 58].

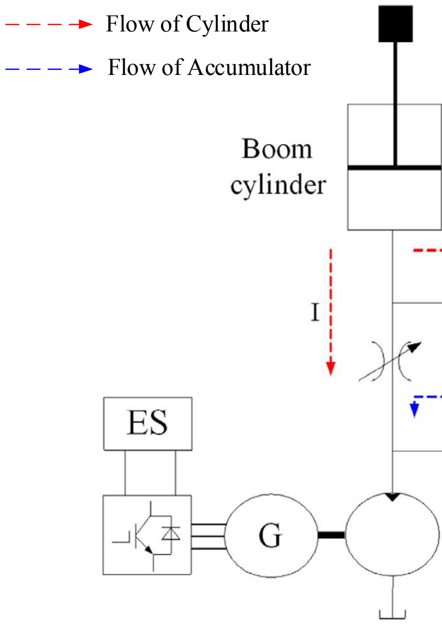


Fig. 2-20 ERS of boom system with additional hydraulic accumulator. [36]

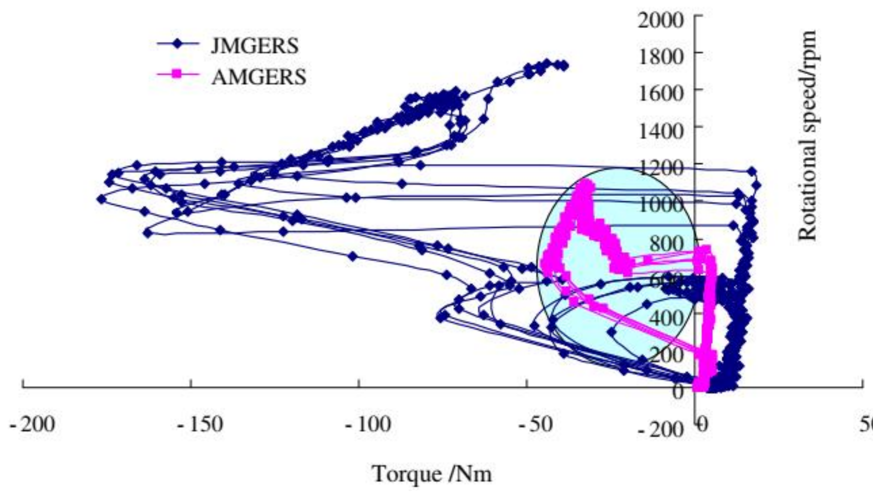


Fig. 2-21 Distribution of the working points of the generator with the hydraulic accumulator (AMGERS) and without hydraulic accumulator (JMGERS). [37]

Table 2-2 Technology summary table of ERS using electrical storage.

Ref.	Novelty	Energy Regeneration Efficiency	Power Consumption Reduction	Merits	Demerits
[46]	First ERS using hydraulic pump/motor.	-	35%	- Stored energy was utilized via an electric motor to assist the engine - Engine worked in low-speed area with high efficiency combustion.	- High energy losses due to the energy had to be converted to different types
[47]	A dynamic-work-point strategy to maintain constantly engine power	-	-	- The engine worked in high efficiency area. - Increased the service life of capacitor.	- Complicated system structure. - Required more control variables.
[50]	A new electric HE using an EHA system included a hydraulic motor/pump and electrical motor/generator	-	↓ 50.15%	- Reduced energy loss by using the EHA system.	- Low dynamic response - Suitable for the small size HE.
[22]	Power controller based on changing SOC threshold to ensure balance energy of engine and supercapacitor	-	↓ 24%	- Analyzed and selected the best structure with shortest expected payback period. - Reduced fuel consumption.	- Results need to be verified on bigger size HE to show the effectiveness of proposed controllers.
[58]	A new ERS structure with an additional hydraulic accumulator.	41%	-	- Increased the efficiency and downsize of generator. - Take advantage of energy storage sources	- Complicated control strategy. - Required new generators with high efficiency and small volume.
[49]	A new structure of ERS by using a throttle valve.	48.7%	-	- Improved cylinder control performance. - Reduced the generator capacity.	- Required big size of components
[51]	A control strategy for motor speed based on the real system [50]	-	47.8%	- Significantly reduces energy consumption.	- Low regenerated energy. - The system has not been verified with the load condition
[48]	A control strategy with load torque observation and flow compensation to enhance the	64.5%	-	- Improved the dynamic performance. - High energy regeneration efficiency.	- Required large sizes generator and hydraulic motor.

	performance of ERSs				
[30]	A control strategy based on pressure of accumulator to guarantee the minimum and maximum recovery times	36%	-	- Capacity of generator and hydraulic motor can be decreased 65%.	- Complicated system structure. - Many factors must be considered during moving down process.
[57]	A new electric HE using combination of a servo motor and a variable displacement pump	-	28.5% - 33%	- The energy efficiency of power source could achieve up to 40% - Reduced power consumption.	- Energy recovery efficiency has not been considered
[29]	ERS using a hydraulic accumulator and a valve–motor–generator	58%	-	- Generator could work continuously and efficiently. - Reduced the cost.	- Efficiency of system should be demonstrated experimentally
[28]	ERS using flow control valve and hydraulic motor was placed directly to the output port of the boom cylinder.	33.8% - 57.4%	-	- The setup power of generator could be reduced and guarantee system safety by using flow control valve. - Reduced the energy loss at the main control valve.	- Requires complex control strategies.

2.3.2. *ERS using hydraulic storage*

In hydraulic ERS, accumulators serve as hydraulic energy storage devices as well as shock absorbers and standby power sources. Fig. 2-22 shows the working principle of ERS using hydraulic storage. The biggest advantage when using a hydraulic accumulator is that it can easily be integrated and operated in the existing hydraulic circuit of HHEs. The hydraulic accumulator is normally attached directly to the tank return port of the proportional directional valve. When the boom cylinder moves down, the flow rate in the bore chamber will go through the control valve and can be directly recovered in the accumulator. Therefore, hydraulic ERSs can reduce losses during the energy recovery process which often occurs in electrical ERS because of transferring from hydraulic energy to electric energy. Most of the used accumulators have been charged with pressured nitrogen from the beginning. The energy is stored by being compressed to high pressure inside the accumulator. So that recovered energy can be used immediately to actuators in emergencies.

The energy regeneration efficiency of hydraulic ERS is proportional to the volume of the hydraulic accumulator. The larger size can recover more energy and vice versa. Hence, the limited energy storage density of hydraulic accumulators is a major flaw when compared to ERSs using electrical storage. The hydraulic ERS is particularly suitable for medium and small-sized excavators where power requirement is within the installation space. In addition, the difference in required power during the boom cylinder moving up and down leads to a challenge for reusing the recovered energy. Based on the above analysis, several researchers have come up with solutions to still take advantage of the hydraulic system and solve outstanding problems.

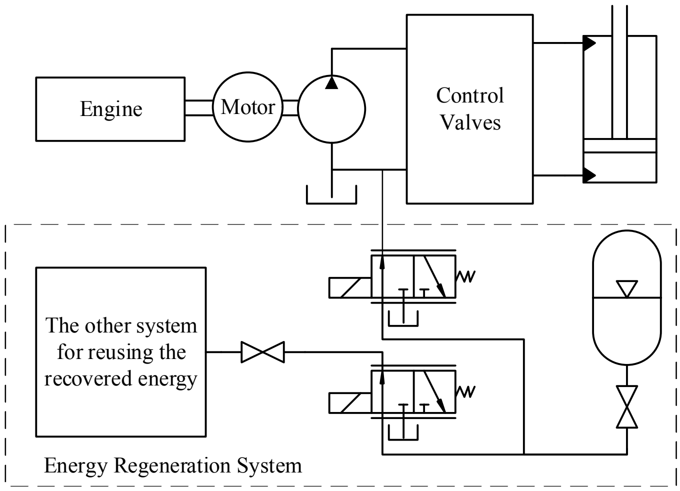


Fig. 2-22 Schematic of the ERS using hydraulic storage.

Bui et al. [52] suggested a new configuration for HE using EHA, an accumulator and two hydraulic transformers as shown in Fig. 2-23. During the moving down process, the potential energy in boom cylinder was converted to mechanical energy by using a variable hydraulic transformer (motor mode) to drive the fixed hydraulic transformer (pump mode) and then, stored the energy in accumulator. The recovered energy could be reused later through the reverse working function of two hydraulic transformer. Based on the load characteristics observer, a flow chart was also proposed for the boom system to achieve more energy-saving. The simulation results indicated that this system could reduce the power consumption. However, this system had high energy loss due to energy conversions (hydraulic – mechanical – hydraulic) and high investigation cost due to the hydraulic transformers. Therefore, it could not apply in commercial products. Knussman et al. [53] from Caterpillar Inc. also used an EHA system which included a variable displacement pump/motor and driven by an engine to control the state of the boom cylinder. A hydraulic pump and an accumulator were integrated into the system to act as a source of pressure oil for the closed-circuit EHA system. Besides, two port of boom cylinder were connected and transferred the flow rate from high pressure chamber to low pressure chamber through a proportional valve (denoted as a regeneration valve). The disclosed hydraulic system may be applicable to any HEs to improve the hydraulic efficiency and performance. Zhang et al. [59] presented an electro-hydraulic system for regenerated the potential energy in two hydraulic accumulators and reused this energy via a pair of pump and motor. In addition, the flow rate in the rod chamber of the cylinder which was normally discharged directly to the tank will be recovered in a low-pressure accumulator. Almost identical to the configuration in [52], Zimmerman et al. [60] suggested an ERSs for boom energy regeneration using three variable hydraulic transformers. However, this system is also too expensive, and it has just been proposed as an idea in the patent. Therefore, its efficiency should be validated by simulation or experiment.

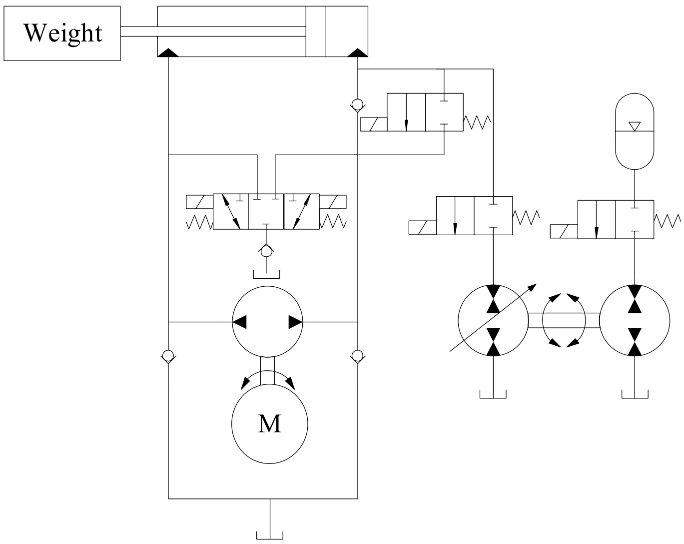


Fig. 2-23 Schematic of the potential energy recovery system of the HHE using the electro-hydraulic actuator (EHA). [52].

Shen et al. [61] used a Common Pressure Rail (CPR) which is one kind of the most typical off-road vehicles to analyze the influences of different control methods to the HE as shown in Fig 2-24. The fuel consumption can be reduced using dynamic programming (DP) and DP also provides a standard to compare different control methods. Nonetheless, with the unknown working cycle, this method cannot achieve good performance. Therefore, for practical applications, three rule-based control strategies were proposed. A strategy called adjustable single point under quasi constant pressure combined the decoupling relationship between the system dynamic with the structure characteristic analysis and the engine. Hence, by using this method, during 5 cycles, the fuel consumption was lowest, which was 44.9 g. Besides, the actuator performance was acceptable. Notably, the fuel consumption can be reduced to 30.1 g since a smaller power can be applied as presented in Fig. 2-25.

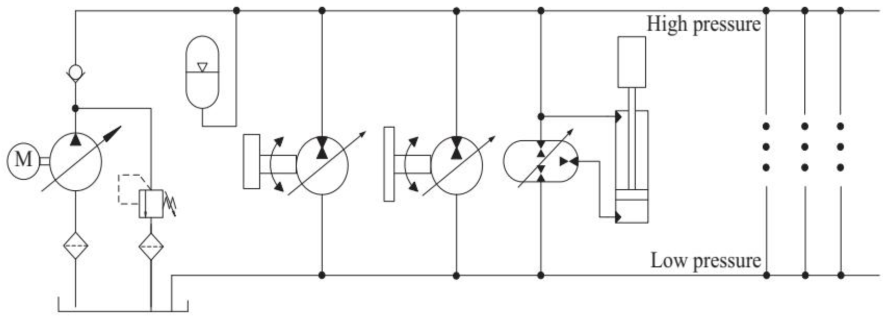


Fig. 2-24 Structure of the Common Pressure Rail system. [41]

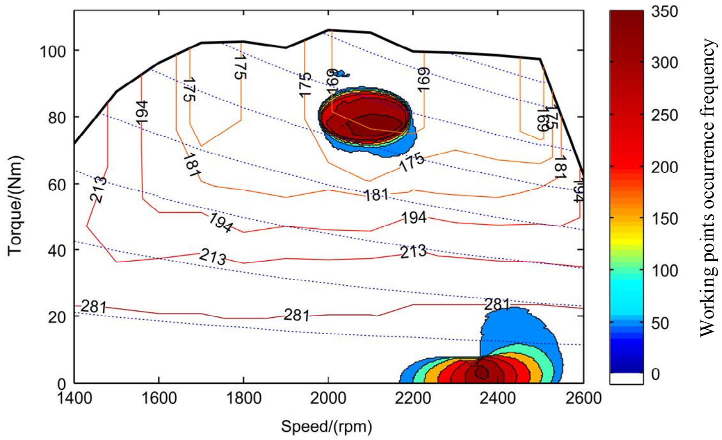


Fig. 2-25 Working points occurrence frequency map under adjustable single point strategy. [61]

Ge et al. [26, 62] proposed a ERS scheme with a hydraulic accumulator and an energy conversion cylinder as presented in Fig. 2-26. In this configuration, the ERS of the excavator's actuator can be saved and reutilized while the cost and installed power are not increased significantly. Based on the multidisciplinary dynamic model of the HE, the influence of the accumulator parameters on the ratio of the energy recovery was investigated. Their results demonstrated that under the lowering process, more than 75.9% of the potential energy in boom system can be recovered into the accumulator with the new ERS. Furthermore, the pump's required power can be decreased by 52% under a certain lifting process as shown in Fig. 2-27. Then, a 76t HE system was built and tested using this fundamental. The energy consumption and the carbon dioxide emissions can be reduced significantly, i.e. 238 kJ under a cycle and 28088.4 kg (emissions) per year, respectively. This study obtained remarkable achievements in energy-saving as well as emission-reduction. Moreover, this scheme can be used in different types of construction machines.

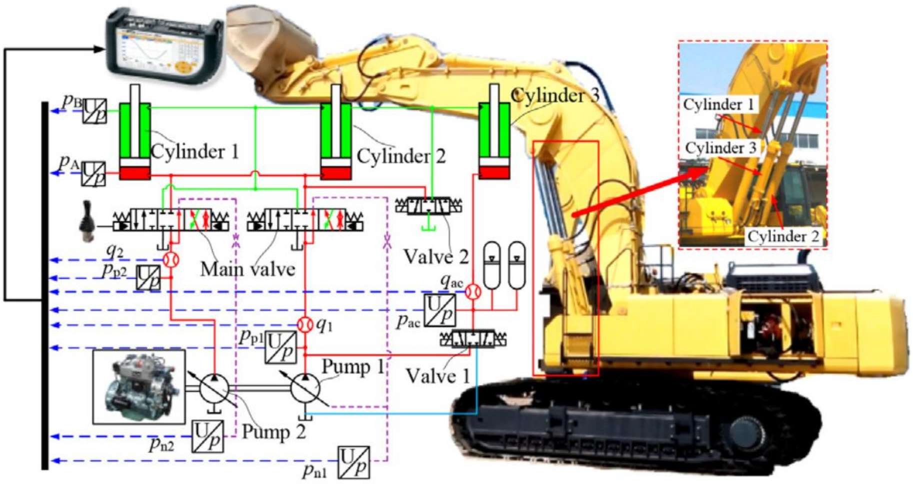


Fig. 2-26 Working principle of the balance boom cylinder system. [26]

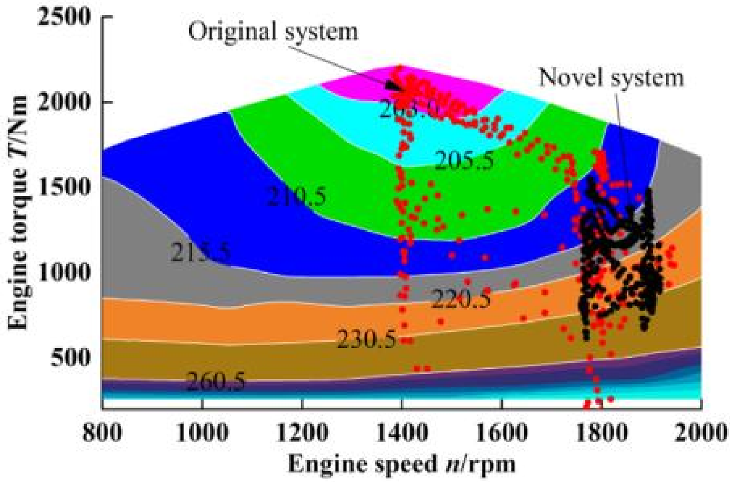


Fig. 2-27 Operating points over five excavation cycles. [26]

Chen et al. [27] proposed a new ERS based on a closed-circuit hydrostatic transmission and implemented a hydraulic accumulator as main energy storage element to store the potential energy of the boom system as presented in Fig. 2-28. During the lifting process, the flow rate in the rodless chamber was supplied from the accumulator through the Pump-Motor 1(PM 1) and the rod chamber through the Pump-Motor 2(PM 2). The power from the accumulator could be compensated or regenerated by using the permanent magnet brushless DC motor (PMBLDC) depend on the load condition (compensate with high load and regenerate with low load). In the process of descending, the flow in rodless chamber was divided into 2 parts, one was supplied to the rod chamber and the rest was recovered to the accumulator through PM 2 and PM 1, respectively. The results indicated the effectiveness of the proposed system, and the experiment platform can achieve efficiency varied from 60% to 68.2% depends on working conditions. However, the disadvantage of this system is that it is expensive because of using two PM and PMBLDC. Besides, the system performance is highly dependent on the initial pressure of the accumulator. If the pressure of accumulator is high, the system cannot regenerate the energy.

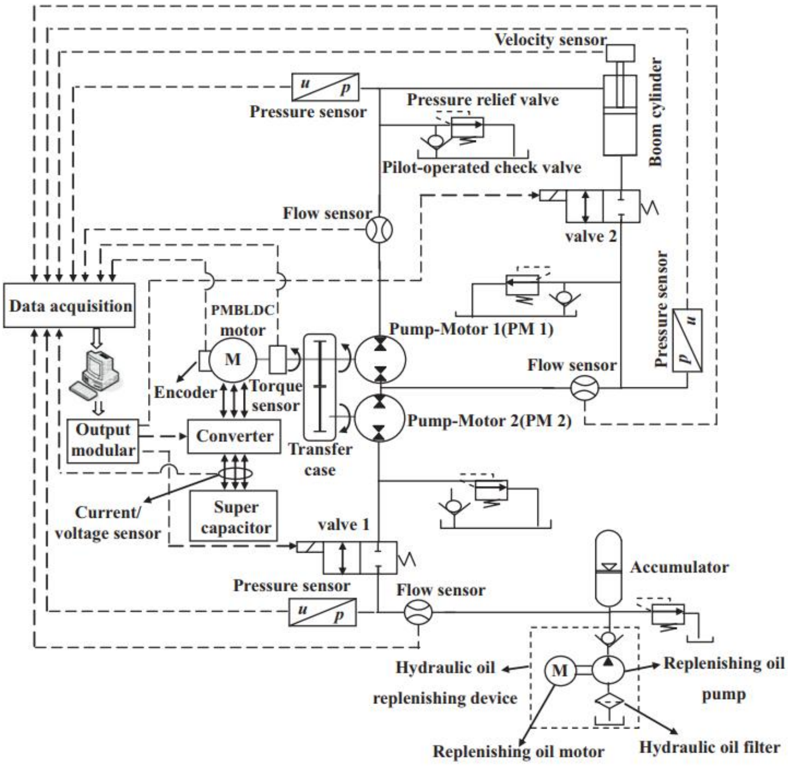


Fig. 2-28 Schematic diagram of the closed-circuit gravitational potential energy regeneration system (GPERS) of the boom. [44]

Xia et al. [63] proposed a new configuration of ERS using three-chamber hydraulic cylinder as shown in Fig. 2-29. A hydraulic accumulator is directly connected to one chamber (port C). The main driving circuit was connected to the other two chambers (Ports A and B). During the moving down process, the potential energy in chamber C was charged into the hydraulic accumulator. In the next cycle, the stored energy in the accumulator is released to support the main pump in the lifting process as shown in Fig. 2-30. To verify the effectiveness of this system, a real test bench based on a 6-ton hydraulic excavator was performed. The experimental results showed that 50.1% energy consumption of the boom and 64.9% peak power of the power source can be reduced in the proposed system compared with the double-chamber system. This design can be widely used in all kinds of devices using hydraulic cylinders. However, the initial pressure of the hydraulic accumulator affected the energy saving efficiency. In addition, it could be the causes of additional throttling losses in the main circuit and reducing the energy regeneration efficiency.

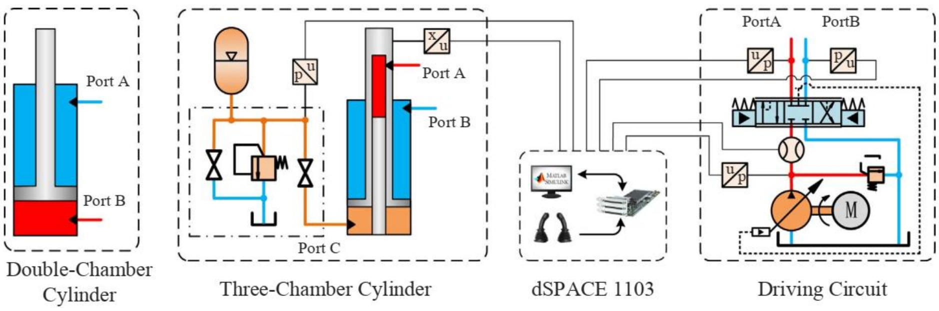


Fig. 2-29 Test schematic of the double and three-chamber cylinder systems. [45]

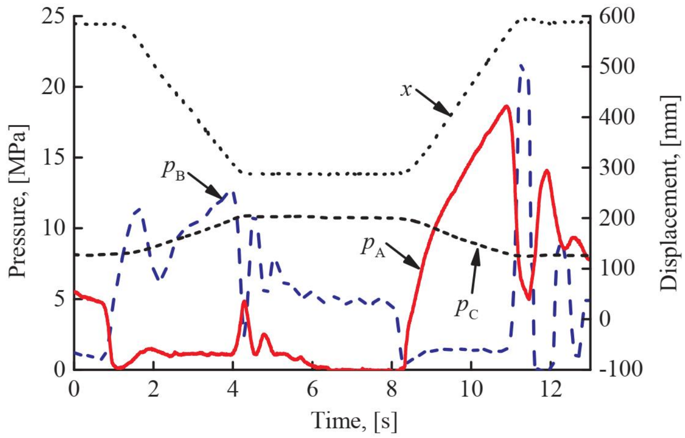


Fig. 2-30 Pressures and displacement of three chambers cylinder. [63]

Ge et al. [55] proposed a novel-designed asymmetric pump to decrease the energy consumption of a HE boom system as shown in Fig. 2-31. The pump had three ports, one was connected to an accumulator and the other two of them were connected to the hydraulic cylinder. Hence, this system could recover the potential energy directly and the unequal flow rates of the single rod cylinder could basically be matched. The working principle and structure of the pump were presented in Fig. 2-32. Furthermore, an experiment test bench of the two systems had been fabricated. The results showed that the proposed system could recover and reuse about 82.7% of the potential energy. Compared with an IMV system, the power consumption during the lifting process could be decreased by 76.1%. Moreover, during the entire working cycle, reduced energy consumption could be reached by 75.0%. Not only hydraulic excavators but also all types of heavy-duty construction machinery could use this configuration to improve the economical fuel.

Finally, a comparison of ERSs using hydraulic storage is then carried out and analyzed in Table 2-3. Recent researches are focusing on developing new energy recovery elements that help solve the problems such limited capacity of the hydraulic accumulator and the pressured flow rate which prevents the cylinder from moving. Hence, the hydraulic ERSs have high recovery efficiency and are being improved over time.

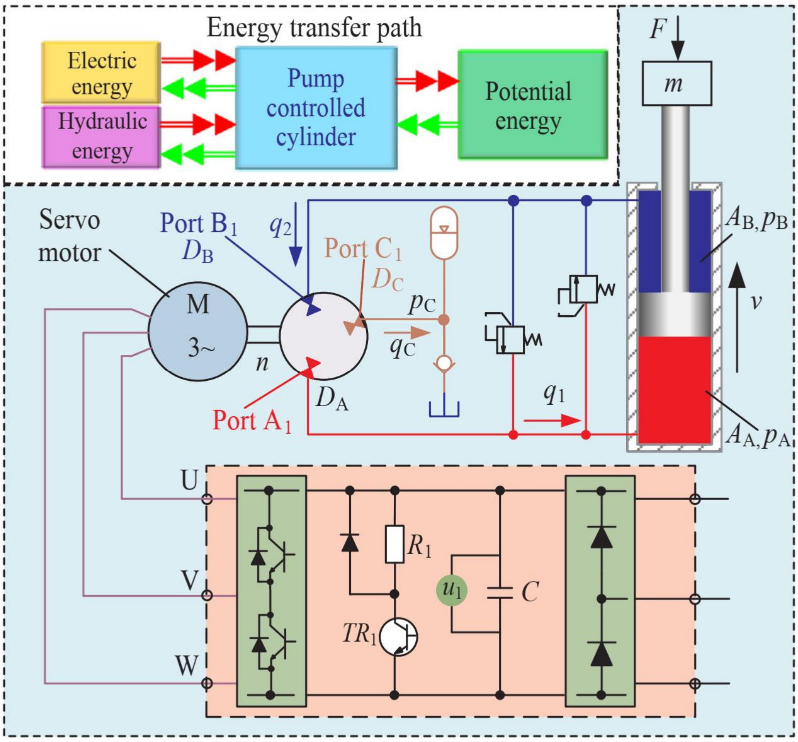


Fig. 2-31 Principle and structure of the novel-designed asymmetric pump system. [55]

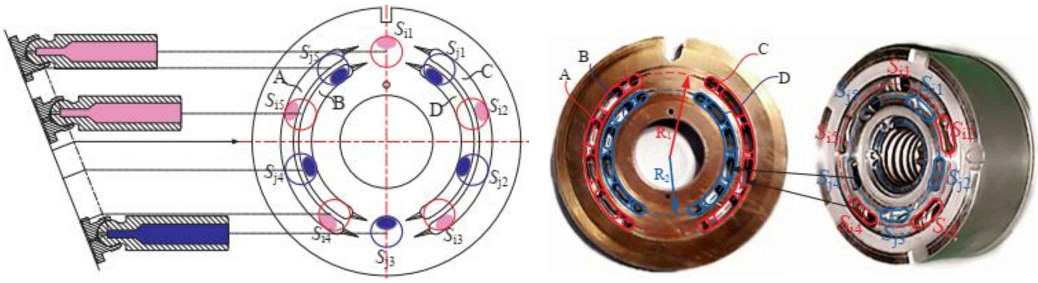


Fig. 2-32 Working principle and the image of the valve plate and cylinder block. [55]

Table 2-3 Technology summary table of ERS using hydraulic storage.

Ref.	Novelty	Energy Regeneration Efficiency	Power Consumption Reduction	Merits	Demerits
[64]	ERS using load sensing system and an assist accumulator.	18%	-	- The system can recover and reutilize energy - Reduce the pump supply energy and work losses	- It is impossible to control the energy recovered in the accumulator during discharge
[65]	ERS using accumulator and a hydraulic pump/motor.	37%	-	- Throttle losses were low.	- During the energy recovery, the engine was still needed to drive the hydraulic motor.
[66]	A digital flow control unit consists of two individually adjustable control edges containing five	45%	-	- Directly recovery and store the energy in accumulators.	- Not suitable with variable load conditions. - Occupied a lot of installation area

	poppet-type on/off valves for flows division.				
[52]	New ERS using hydraulic transformer and EHA system	-	↓1.76%	- Reduced pump's displacement. - Stored energy in accumulator could be reused through hydraulic transformer.	- Low saving energy. - Not feasible with commercial products.
[61]	Secondary components (pump/motor and Hydraulic Transformer)	-	↓38.2%	- Reduced power consumption	- Not consider the energy regeneration efficiency. - Too expensive.
[67]	ERS using a three-chamber cylinder and EHA system	-	↓26%	- Directly recovery and store the energy in accumulators. - Low energy losses	- Low dynamic response - Required big engine with high working torque
[68]	ERS using the STEAM system (connected actuators with three level pressures through valves) and IMV system.	54%	-	- Combines the advantages of STEAM system, IMV system and hydraulic transformer	- Complicated system. - Many control variables during operation
[27]	ERS using a closed-circuit hydrostatic transmission	60% - 68.2%	-	- High energy regeneration efficiency. - Good control performance.	- High cost. - Complicated system structure.
[69]	ERS using two pump/motor and an accumulator	67.5 %	-	- High energy regeneration efficiency. - Regenerated the energy in three actuators (boom, arm, bucket)	- High cost. - Take up a lot of installation space.
[63]	ERS using three chambers cylinder and accumulator.	-	↓64.9%	- High energy saving efficiency. - Simple structure and low cost.	- Initial pressure of accumulator affected energy saving performance
[55]	ERS using a novel asymmetric pump	82.7%	↓75%	- High energy regeneration and energy saving efficiencies. - Direct energy conversion - Reduced pressure shock and oscillation.	- Low dynamic response. - Each actuator had to use an independent pump.
[70]	ERS using a hydro-pneumatic accumulator, a	-	↓10%	- Considered the energy regeneration in both boom and swing system.	- The main pump had to supply flow rate to the cylinders during the energy recovery

	hydro-motor, and a loading pump.				
[26]	ERS using balanced hydraulic cylinder.	75.9%	-	- High energy regeneration efficiency. - Directly regenerate the energy without auxiliary links	- Initial pressure of accumulator affected energy saving performance
[62]	ERS using third cylinder to recover the energy.	41.6%	-	- Directly regenerate and reuse the potential energy.	- Initial pressure of accumulator affected energy saving performance

2.3.3. ERS using mechanical storage

A flywheel is a rotating mechanical device used to store rotating energy. The flywheel has a large inertia torque and resists changes in rotation speed. The amount of energy stored in a flywheel is proportional to the square of its rotation speed. Energy is transferred to a flywheel by applying torque to it and then increases the rotation speed and stored energy. In contrast, the flywheel releases stored energy by applying torque to the mechanical load, resulting in reducing rotation speed. Based on the typical characteristics of the mechanical flywheel, Jiansong Li et al. [71] proposed a new mechanical ERS integrating a flywheel, a variable hydraulic pump/motor and a regeneration flow control valve as shown in Fig. 2-33. When the boom cylinder moved down, the regeneration flow control valve is opened and the flow in the bore chamber flows to the rod chamber. The remained flow rate rotates the hydraulic motor and converts to mechanical energy stored in the flywheel. When the boom cylinder moves up, the stored energy rotates the hydraulic pump and supplies the flow rate to the system. With this proposed system, the author not only studied the issue of energy recovery but also the issue of reusing the recovered energy. The simulation results showed that the overall efficiency could be reached up to 62%. However, this system has only been verified by the simulation model. The actual efficiency of the system needs to be validated through a real experiment system.

The main disadvantage of flywheels that competes with other storage components such as a battery or hydraulic accumulator is the relatively high standing losses and high cost. The self-discharge rates are high in many flywheels i.e. about 20% of the stored capacity per hour. Besides, the characteristics of the actuators in the HE were a high-frequency operation, variant displacement, and unstable velocity. But to store energy in the flywheel, the rotation speed of the hydraulic motor must be bigger than the current speed of the flywheel. Therefore, the imposition of flywheels in renewable energy recovery systems is a major challenge for researchers.

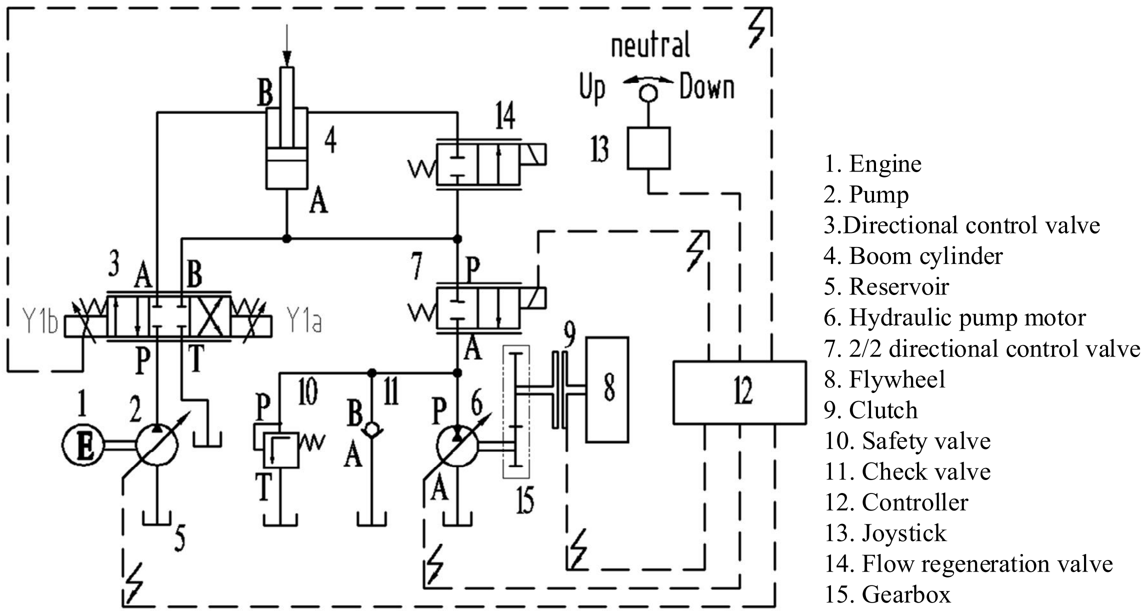


Fig. 2-33 Structure of a flywheel mechanical ERS. [53]

2.3.4. Types of Swing energy regeneration technologies

While there are many studies on the ERSs for the boom system, the number of studies for the ERSs in the swing system has been very limited. The reason was that the design of the ERSs for the swing system is more complicated than the boom system, the ERSs must be able to operate on both sides of the hydraulic motor during the operation. Besides, the recoverable energy during is not constant. It depends on the angle of rotation and the speed of swing motor usually takes place over a short time. However, the energy of the swing system accounts for 25% of the total potential energy of the HE. Therefore, the study of the ERSs for the swing systems has been extremely necessary. In the swing system, there are two possible energy harvesting times: acceleration or deceleration. These processes are normally operated for a short period of time and with a high working frequency.

Lee et al. [72] suggested a hydraulic circuit for the swing system using an accumulator and a directional valve. During the deceleration process, the flow rate in high pressure port of the swing motor was stored in an accumulator through the relief valve. The regenerated energy was reused into the system during the acceleration process via the directional control valve as shown in Fig. 2-34. The results showed that the proposed system can increase working efficiency more than that of the conventional system. The energy efficiency can reach to 18.5%. However, this structure is highly dependent on setting pressure of the relief valves. High setting pressure value reduces the recovery performance of the system. In the case of small setting value, it increases energy consumption because the pump has to supply the system while charging the accumulator. Therefore, this approach has proved unsuitable for commercial products.

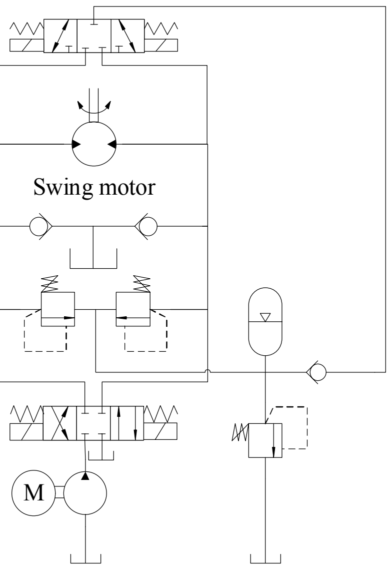


Fig. 2-34 Schematic of hydraulic ERS swing system. [72]

Chowdhury et al. [54] replaced the conventional hydraulic circuit by using an EHA system as shown in Fig. 2-35. Then, the rotation speed and angle of the rotating motor can be directly controlled via the bi-directional pump and motor. In addition, two pairs of the pump and hydraulic motor were integrated to regenerate and reuse the energy during the deceleration. The authors conducted a series of simulations to analyze the relationship between moment of inertia and the capacity of the hydraulic accumulator. Finally, the maximum saving energy could achieve up to 23%. However, this system was expensive and high loss energy due to using multiple hydraulic motors and pumps. In addition, low energy saving efficiency leads to long payback times and low commercialization.

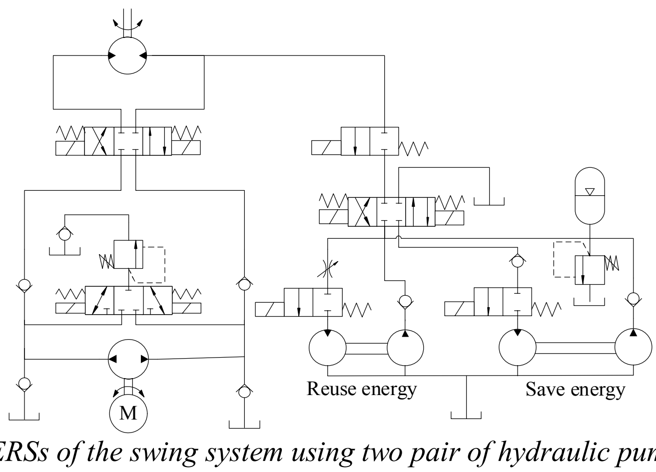


Fig. 2-35 The ERSs of the swing system using two pair of hydraulic pump and motor. [54]

Xiao et al. [24] proposed a new hydraulic system for the swing system with a hydraulic accumulator and two flow control valve as shown in Fig. 2-36. This system had some similarities with the presented system in a previous patent [73]. The kinetic energy is recovered directly into the accumulator and reused through some directional valves. When the swing system decelerates, the flow rate from the variable displacement hydraulic motor is controlled by the flow control valve V1 and charged to the hydraulic accumulator. In subsequent cycles, the stored flow in the hydraulic accumulator is supplied to the system via the flow control valve 11 (4 ports and 3 positions). Besides, the author was also concerned about the oscillation and energy regeneration efficiency of the proposed system. They designed a control strategy based on a PID controller. Therefore, the proposed system had a much lower cost than the electric ERS system and the energy regeneration efficiency could reach up to 33.4%.

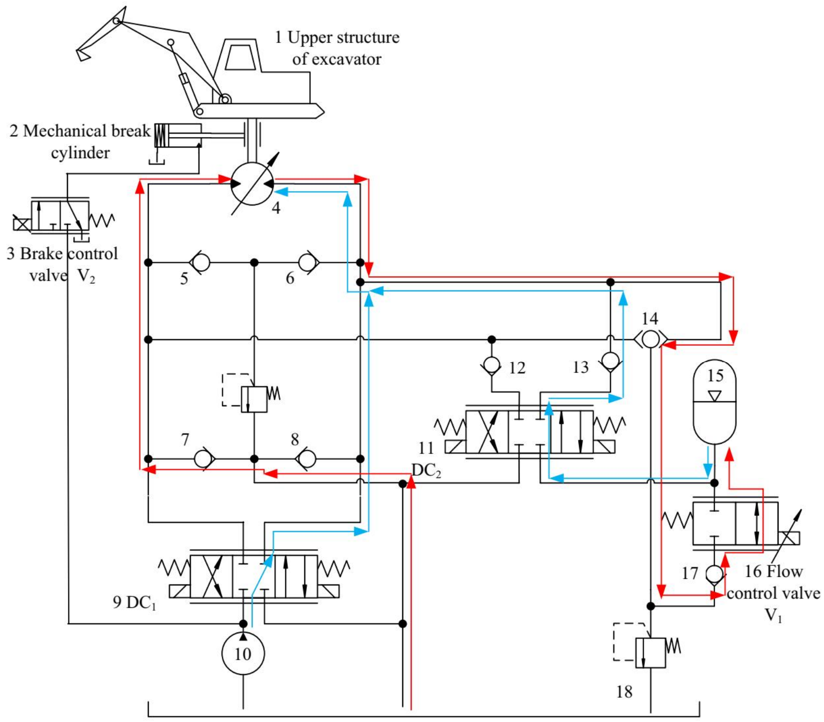


Fig. 2-36 Hydraulic circuit of the ERS system using an accumulator and a flow control valve. [24]

Based on the above research [24], Xiao et al. [25] continued to develop ERS to improve energy regeneration efficiency. Two independent accumulators with different initial pressures were used for the hydraulic ERSs of the swing system as shown in Fig. 2-37. The flow rate from the hydraulic motor could be charged into one of the two hydraulic accumulators depending on the system pressure. This helped the system to overcome the problem of the previous one accumulator system as the pressure of the tank is too high which can hinder the movement of the rotating system during operation. Experimental results demonstrated the effectiveness of the proposed system. The energy regeneration efficiency was improved by up to 56%. Zhang et al. [74] also presented a configuration of hydraulic ERSs for the swing system using two accumulators. Depended on the pressure of the swing hydraulic motor, the flow rate will be selected to charge into the specific accumulator. Besides, one accumulator can be charged, and another one can be discharged at the same time during the operation.

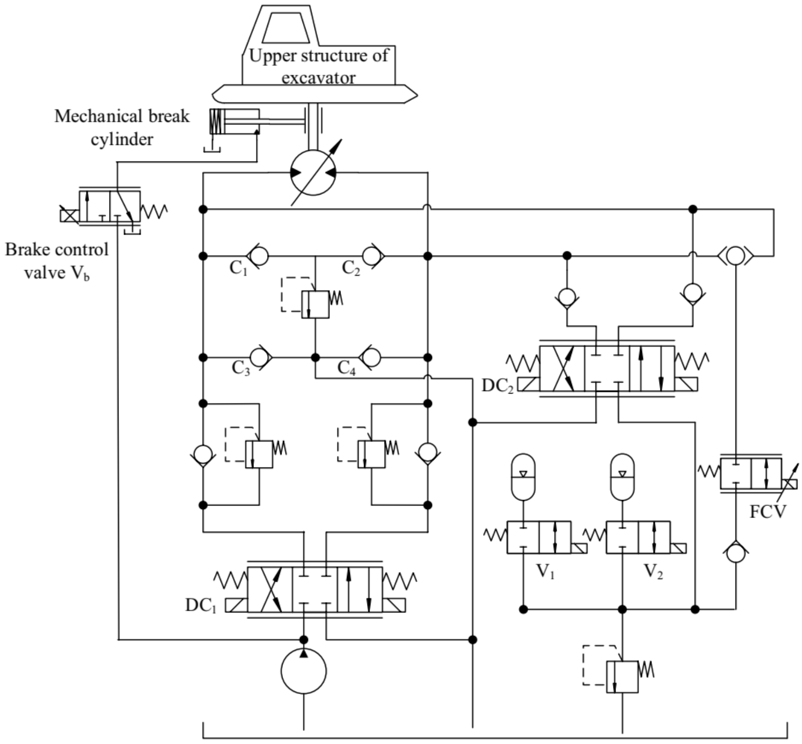


Fig. 2-37 Hydraulic circuit of the ERS system using two independence accumulators. [25]

During the acceleration process, Zheng et al. [75] proposed a new ERS hydraulic circuit for swing system using an accumulator and two independent directional control valves. The potential energy of swing motor was stored in the accumulator and released to support the pump in next cycles. The proposed system could achieve 28.5% energy regeneration efficiency and reduce the energy loss. Zhang et al. [76] added two pressure reducing valves to hydraulic system which could control the displacement of main pump due to the working condition. During swing motor acceleration, the flow rate of main pump was controlled to match with required flow from the swing motor, thereby the motor overflow and system response time were reduced. However, this system required a new directional control valve which could guarantee that the motor outlet connected to the tank in the closed position. This was difficult to do in real conditions due to the instability and noise of swing system. Kim et al. [77] registered a patent named swing relief ERS which included a hydraulic motor and pump connected with the engine through a planetary gear. Potential energy was stored into the accumulator through a relief valve, then reused through the hydraulic motor to support the engine. However, the use of a relief valve caused large energy losses during the operation. H. Ren et al. [78] integrated four directional control valves, two shuttle valves and an accumulator to the swing system. During the acceleration, the accumulator was connected to the high-pressure port side of swing motor to save the acceleration energy via the controlled valves. Then, in next cycle, the stored energy was automatically released to drive the hydraulic motor as shown in Fig. 2-38. A real test bench was built to validate the effectiveness of proposed system. The results showed that the energy regeneration efficiency was up to 80%. In addition, the pressure sock and motor speed could be reduced to improve the control performance. Lin T. [79] presented a new ERS for swing system using hydraulic motor and generator. During the operation, the check valves was opened to connect the hydraulic motor with high pressure port of swing motor. Then, this system could recover both the orifice loss of the relief valve and the kinetic energy at the acceleration and deceleration processes. The simulation results indicated that this system could overcome the anti-reverse and achieve 38% energy saving efficiency.

Table 2-4 then summarizes the current energy regeneration technologies of swing system during the acceleration and deceleration processes. It indicated that most ERSs use accumulators as energy storage devices due to the advantages of hydraulic ERSs (such as low energy loss, and the rapid energy storage). The factors are very consistent with the properties of the swing system as described above.

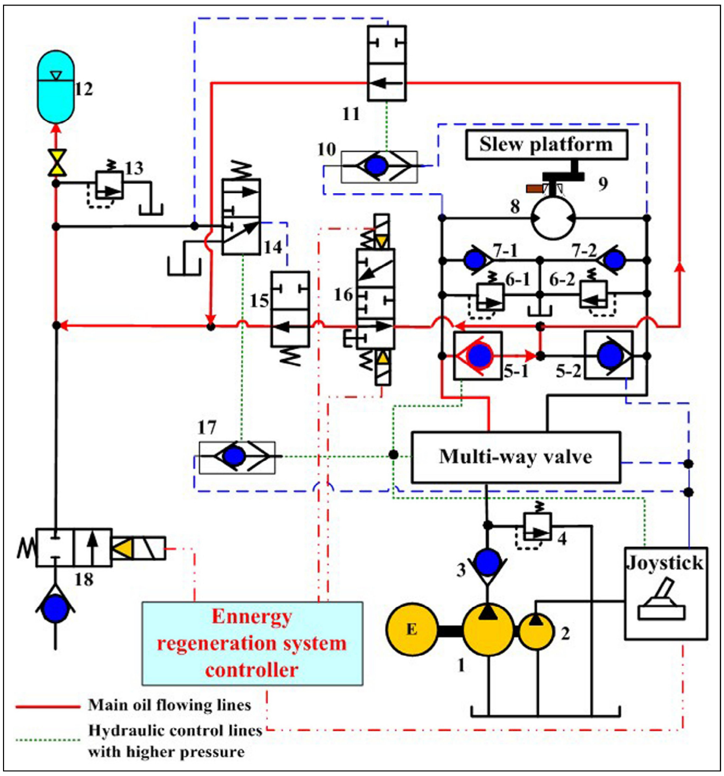


Fig. 2-38 Proposed ERS system using accumulator for swing acceleration process. [62]

Table 2-4 Technology summary table of swing ERS.

Ref.	Novelty	Energy Regeneration Efficiency	Power Consumption Reduction	Merits	Demerits
[72]	ERS using hydraulic accumulator and a directional valve.	18.5%	-	- Directly stored the swing energy in accumulator. - The stored energy could be reused.	- Initial pressure of accumulator affected to energy saving efficiency.
[54]	ERS using two pairs of the hydraulic pump and motor	22.75%	-		- The structure was cumbersome and ineffective - Long expected payback periods

[24]	ERS using a hydraulic accumulator and flow control valves	33.4%	9.2%	- Reduced the fluctuation and improved energy regeneration efficiency.	- Initial pressure of accumulator affected to energy saving efficiency.
[25]	ERS using two independent accumulators	23% to 56%	-	- Easy to integrate in a real excavator.	- Complicated control strategy. - Many factors must be considered in the energy recovery process.
[75]	ERS using an accumulator and two independent control valves	28.5%	-	- Simple structure	- The system only could work in the case of the pressure in accumulator greater than system pressure.
[78]	ERS using four directional control valve two shuttle valves and an accumulator	80%	16.5%	- High energy regeneration efficiency - Reduced pressure sock and motor speed.	- Not yet consider the energy regeneration efficiency during the brake
[79]	ERS using hydraulic motor and generator		38%	- Can regenerate the energy in both acceleration and deceleration processes.	- High energy loss.

2.4. Challenges

Based on the above analysis, it can be seen that the HHE still emits harmful CO2 emissions into the atmosphere, which is usually the main thing people want to avoid when buying an electric excavator. Having both an electric motor and an ICE means that two drivetrains are needed with their own specific maintenance requirements, which has the potential to complicate matters when it comes to repairs. The price gap between ICE excavators and HHEs isn't as big as the gap between ICE excavators and electric excavators, they are still more expensive, making cost one of the main disadvantages of HHE. The batteries used in electrified excavators don't take too kindly to extreme temperatures: too much heat will speed up battery degradation, and extreme cold will negatively affect the battery's range. Cold temperatures can also cause hybrid batteries to require more time to reach operating temperature, which also causes the excavator's ICE to expend more energy, leading to poorer fuel consumption. Extracting the reusable elements from batteries is a difficult and expensive process, meaning there's a long way to go before it's done on a wide, cost-effective and environmentally friendly scale.

Meanwhile, energy recovery systems tend to become more complex and use more auxiliary equipment. For example, in an electrical ERS, in addition to the main energy recovery components (such as the hydraulic motor and generator), the system requires other devices (such as control valve(s) and accumulator(s)) to help avoid pressure socks and improve the actuators' performance. Similarly, in a hydraulic ERS, direct recovery of potential or kinetic energy in the boom or swing system, respectively, into the accumulator is ineffective because increased pressure in the accumulator could interfere with the actuators' movement. Hydraulic ERSs therefore need to use throttle valves or hydraulic transformers to ensure the safe and stable operation. The same level of requirements goes for the mechanical system. Hence, complex ERSs could lead to an increased energy loss and/or a decreased regeneration efficiency. Besides, ERSs requires space to install new devices on excavators, resulting in weight gain and subsequently, higher power consumption at the swing and traveling systems.

Selection of energy storage devices in ERSs is also a challenging task. Main options available in the market are known as batteries, capacitors, accumulators and flywheel. Batteries offer long lifetime and high energy density. However, power conversion from batteries to electric motor/generator, and vice versa, normally take 2-3 seconds to match the system requirements [15] whilst the actuators in HEs work continuously. Although capacitors or supercapacitors can be charged and discharged quickly, they have shorter working life and higher cost. Accumulators are capable of quickly recovering energy. Nevertheless, any increase in storing capacity leads to an increase in the accumulator volume, preventing its applicability. Alternative solution is known as mechanical flywheels. Nonetheless, flywheels with higher energy loss due to friction could not hold the recovered energy for long periods of time.

Control strategies plays a very important role in the development of ERSs for HEs. The system configuration no matter how good it is, needs to be operated accurately and flexibly to achieve high efficiency. Load conditions, SOC of batteries/supercapacitors, speed, flow rate and/or pressure of active components (such as pumps, motors, generators, accumulators and flywheels) in ERSs should be considered and properly controlled to enable an optimal performance. In addition, performance and/or efficiency maps and operation constraints of the key components in combination with real-time updates of their states are utilized in optimization and decision making of EMSs to ensure the optimal operation of these components. This therefore requires a lot more data from HEs through sensors and communications which might do not work well in harsh environments, leading to a reduction in the system efficiency.

Another challenge in the deployment of ERSs is associated with costs. Manufacturing cost of new HEs integrated ERSs could be much higher than that of conventional HEs and potentially, leading to a long payback time. Therefore, the requirement is to research and propose affordable cost and suitable ERSs for each size of the excavator to trade-off between the investment cost, energy recuperation capability and system efficiency. Moreover, due to the harsh and dusty working environment of HEs, the key ERS components such as motors, generators, batteries and sensors are susceptible to damage and thus, requiring more attention with extra costs for regular maintenances and services. Addressing this problem is also one of the important tasks in developing ERSs.

Chapter 3
ELECTRICAL HYDRAULIC CONTINUALLY VARIABLE POWERTRAIN

3.1. Introduction

Hybrid hydraulic excavators can be categorized as electric hybrid excavators and hydraulic hybrid excavators [24, 25, 80]. An electric hybrid hydraulic excavator uses a battery or supercapacitor as the energy storage unit to store energy. The potential energy or kinetic energy of an actuator can be converted to electric energy by using a generator and saved in the energy storage unit. A hydraulic hybrid excavator uses a hydraulic accumulator as the energy storage unit, in which regenerated energy can also be stored [10]. The stored energy can be reused to assist the engine in running the actuator or to run the actuator directly. In this manner, energy consumption can be reduced.

In this regard, energy regeneration is a key research aspect of hybrid hydraulic excavators. Energy regeneration systems of hybrid hydraulic excavators include electric energy regeneration systems and hydraulic energy regeneration systems [81]. According to Wang T. et al. [8], an EERS for a boom was proposed. In this framework, the hydraulic motor and generator were installed in the return line of the boom system. The performance under no load and loaded conditions were evaluated experimentally, and the efficiency of the hydraulic motor, generator, converter, and super-capacitor was analyzed. The energy recovery efficiency was noted to range from 26% to 33%. A similar energy regeneration system was researched by Wang T. et al. [48]. Both the generator and hydraulic valve were controlled to regenerate energy and reduce the fluctuations of the boom. The energy regeneration system with two independent valves was researched by Yu Y.X. et al. [82]. The energy regeneration efficiency and stability of the boom cylinder can be improved by controlling the two independent valves.

The EERS of an electric forklift system was researched by Minav T. A. et al. [83]. In this system, the pump/motor and generator were the key components for energy regeneration. When the cylinder moved down, the pump/motor functioned as a motor to drive the generator to regenerate energy. When the cylinder moved up, the pump/motor served as a pump to provide flow to the cylinder.

The electric ERS system with a variable hydraulic motor was described in a study by Yu Y.X. et al. [28]. The efficiency of the hydraulic motor and generator was examined to optimize the working points of the hydraulic motor and generator. The energy regeneration prat can operate at the highest efficiency under all conditions. Compared with the conventional energy regeneration system, the improvement of energy regeneration efficiency was 3.2% to 4.1% with the optimal method of energy management strategy.

Several researchers also investigated HERS of hydraulic hybrid systems. According to Ranjan P. et al. [70], a hydraulic accumulator was used to store the regenerated energy. The experiment results showed that the proposed system was 10% more efficient compared to the conventional system. A three-chamber cylinder and hydraulic accumulator boom system were proposed in the study of Hao Y. et al. [84]. In this system, one independent chamber of the cylinder is used to regenerate the potential energy. The experiment results demonstrated that 26.2% to 44.4% of the energy could be regenerated.

Notably, both batteries and hydraulic accumulators can be used as energy regeneration systems, and the EERS and HERS can be combined. According to a study by Lin T. et al. [58], the accumulator-motor-generator regeneration system was discussed and simulated. The gravitational potential energy could be converted to electrical or hydraulic energy, based on the energy management strategy. The accumulator could charge the battery through the hydraulic motor and generator. Simulation results showed that the efficiency of the generator could be increased, and the generator size could be reduced by using the accumulator in the hybrid boom system. An estimated 41% of the potential energy could be regenerated. Subsequently, the authors researched a similar system [30]. The experiment results indicated that the recovery efficiency was approximately 39%, and the hydraulic motor size could be decreased by >65%. An energy regeneration system with a valve, motor/generator, and hydraulic accumulator was researched by Chen Q. et al. [29]. The energy regeneration system could regenerate energy from all the actuators of the excavator. The simulation results indicated that the proposed system could regenerate 58% of the potential energy. The abovementioned studies demonstrated that energy regeneration systems could help save energy in electric hydraulic excavators and hydraulic hybrid excavators. Another key aspect in the context of research on hybrid hydraulic excavators is the electric drive system. An innovative driving system with an electric motor and novel asymmetric pump was researched by Ge L. et al. [55]. The proposed asymmetric pump could serve as a displacement variable pump and realize energy regeneration. Compared with an independent metering circuit, the electric power of the boom system during the moving-up operation could be reduced by 76.1%. Moreover, an electric hydraulic excavator configuration was proposed by Ge L. et al. [57]. In this research, a displacement variable pump driven by a speed-variable electric motor was used as the power source. A control strategy was developed to control the electric motor and pump displacement to decrease energy consumption. The experiment results indicated that the energy-saving ratio ranged from 28.5 to 33%. Although this system could be used in electric hydraulic excavators, long-term continuous operation could not be realized. A multi motor-pumps system was developed by Huang H. et al. [85]. In the proposed system, multi motor-pumps were installed in the system to provide flow, and each pump was driven by the electric motor. With the proposed energy management strategy, 26.97% of energy can be saved in a working cycle. These studies demonstrated that, electric ERS and hydraulic ERS could be used to save energy. However, the energy reuse in the drive mode when using the electric ERS and hydraulic ERS was not investigated, although this aspect influences the energy-saving efficiency of the total system.

Based on the current research, energy regeneration is researched widely. However, the energy reuse of the drive mode is important to decide the energy-saving efficiency of the hydraulic excavator. Therefore, to decrease the energy consumption of engine- driven excavators, an innovative electric hybrid hydraulic excavator is proposed. A displacement variable pump is driven by an electric hybrid system as the powertrain. The electric hybrid system consists of an engine and an electric motor. Both the engine efficiency and hydraulic pump efficiency are considered to enhance the energy-saving efficiency. An electric ERS is implemented in the boom system. In contrast to the previous research, not only energy regeneration but also energy reuse in the drive mode is examined in the present study. In the structure design, both the speed and torque of the engine can be adjusted through the electric motor, hydraulic pump displacement, and planetary gear to improve the efficiency of the engine. The innovative system in this chapter is proposed for the first time.

3.2. System structure

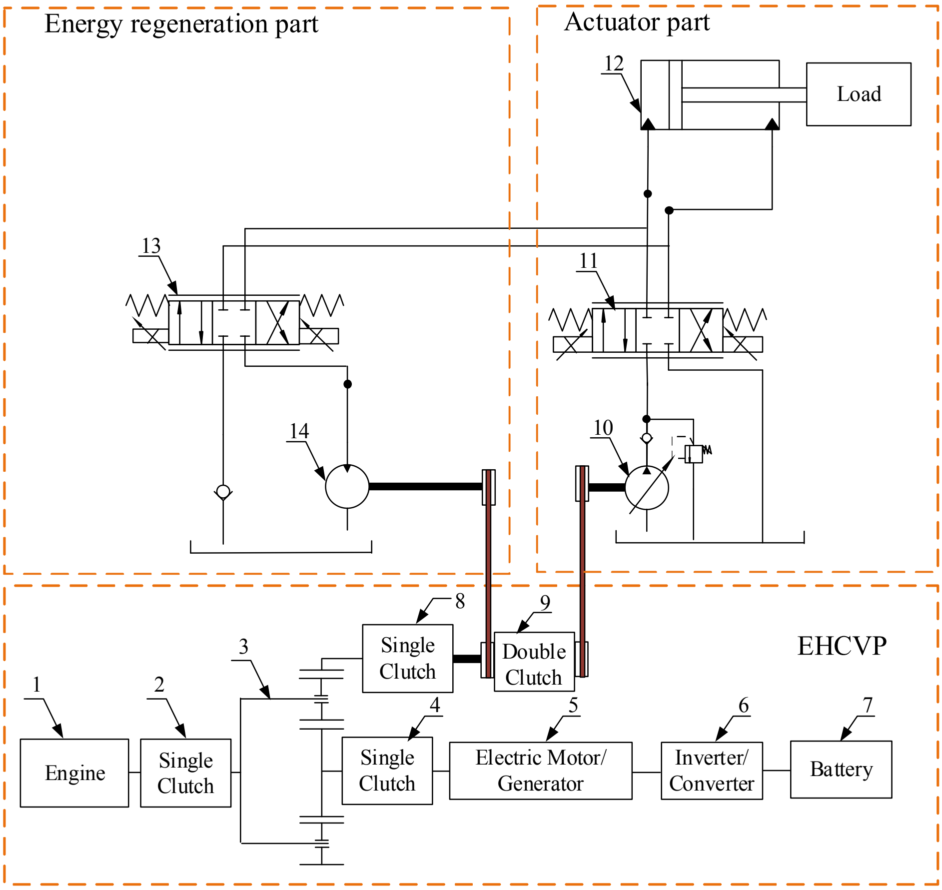


Fig. 3-1 Structure of the proposed boom system with EHCVP.

The overall structure of the proposed EHCVP consists of three main parts: EHCVP, energy regeneration system, and actuator as presented in Fig. 3-1. In the EHCVP part, the engine (1) and the electric motor/generator (5) are the main power sources supplying power for the system through a planetary gear (3) in which the engine, the electric motor/generator, and the hydraulic devices are connected with carrier gear, sun gear, and ring gear, respectively. The speed of power sources is transferred to the hydraulic system by using single clutches (2, 4, 8) depending on the working operation. In addition, a double clutch is integrated at the output shaft of the ring gear to change the connection between the EHCVP and with hydraulic pump (10) or motor (14). In the actuator part, driven by this EHCVP, a variable displacement pump (10) supplies hydraulic flow toward the proportional directional valve (11), whose function is to purposely control the oil direction as desired. Thus, the state of the boom cylinder (12) can be decided by the working position of the proportional directional valve (11). In the regeneration part, a hydraulic motor (14) is installed at the bore chamber line. The combination of a hydraulic motor (14), electric motor/generator (5), and battery inverter (6) helps convert hydraulic energy into electrical energy. With the above structure, the proposed system can operate in four modes: normal mode, hybrid mode, reuse mode, and regeneration mode.

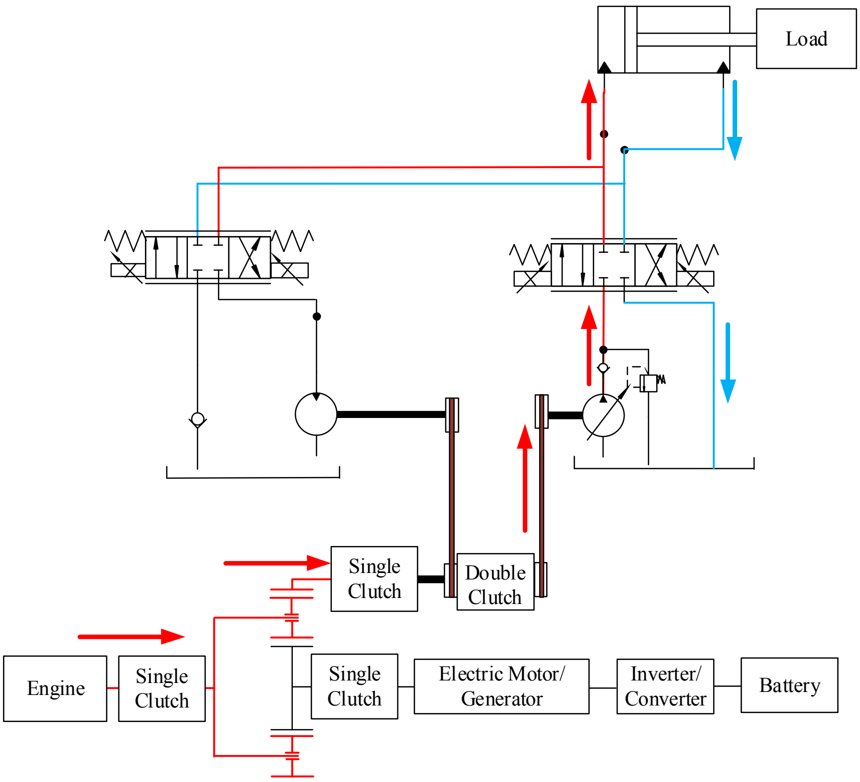


Fig. 3-2 Working principle of EHCVP in normal mode.

Normal mode: the main pump is driven by the ICE without support from the electric motor/generator (Fig. 3-2). The flow rate from the main pump is supplied to the cylinder and its state is controlled by the main control valve. The output flow rate is discharged to the tank. This mode is similar to the conventional HE. Therefore, it cannot reduce energy consumption.

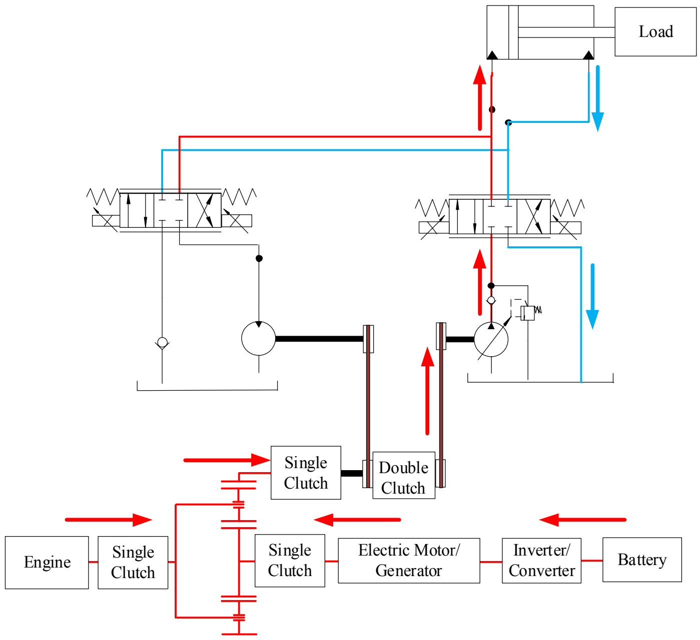


Fig. 3-3 Working principle of EHCVP in hybrid mode.

Hybrid mode: the ICE and electric motor/generator drive the main pump together (Fig. 3-3). The motor/generator can work as a motor or generator, depending on the energy management strategy. The ICE, therefore, can be maintained in a high-efficiency area by changing the speed of the electric motor/generator.

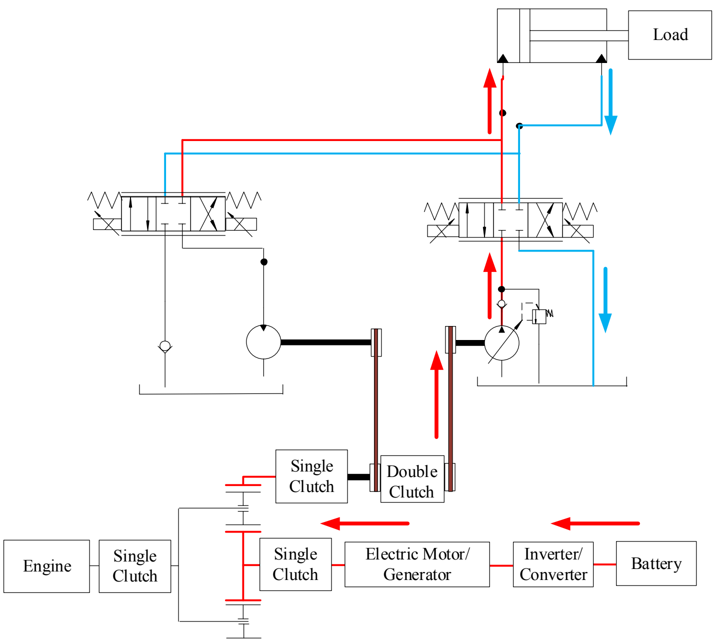


Fig. 3-4 Working principle of EHCVP in reuse mode.

Reuse mode: the stored energy in the battery is supplied to the electric motor/generator working in the motor function (Fig. 3-4). The electric energy is converted to mechanical energy and provided to the main pump.

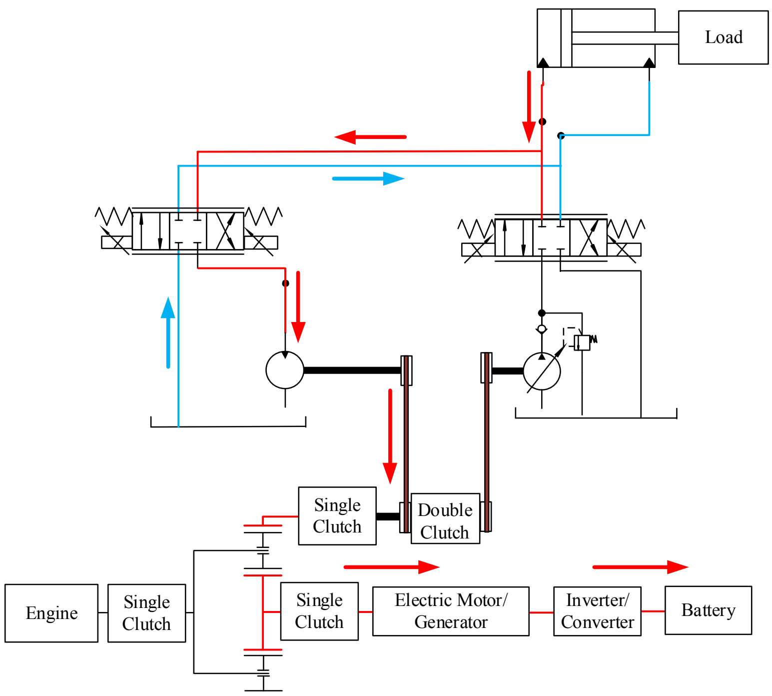


Fig. 3-5 Working principle of EHCVP in regeneration mode.

Regeneration mode: this mode is used for the boom-lowering process (Fig. 3-5). The potential hydraulic energy in the bore chamber is captured and stored in the battery through the hydraulic motor and electric motor/generator.

3.3. Experiment test bench

In the test bench, one cylinder is installed to emulate the boom cylinder to evaluate the performance of the EHCVP (Figs. 3-6, 3-7). The electric motors 1 and 2 emulate the engine and motor/generator, respectively. A double clutch is installed to control the ring gear shaft to be connected to the main pump through belt 2, or the hydraulic motor through belt 1. The energy regeneration part is also set up on the test bench. The system operates in two modes: boom-up and boom-down modes. In the boom-up mode, the main valve operates in the left position, and the double clutch connects the EHCVP to the main pump through belt 2. The EHCVP drives the pump to provide fluid to the rod chamber of the cylinder to move the load up. In boom-down mode, the main valve operates in the middle position, and the energy regeneration valve *Vr* is open. The double clutch connects the hydraulic motor to the EHCVP through belt 1. The energy regeneration valve is open. In this case, electric motor 1 and the ring gear shaft are braked, and electric motor 2 works to emulate the generator, which generates torque to balance the load and control the speed of the hydraulic motor. A speed sensor and torque sensor are installed in each gear shaft. A pressure sensor is installed in the output port of the rod chamber.

Fig. 3-6 Boom cylinder and powertrain in experiment test bench.

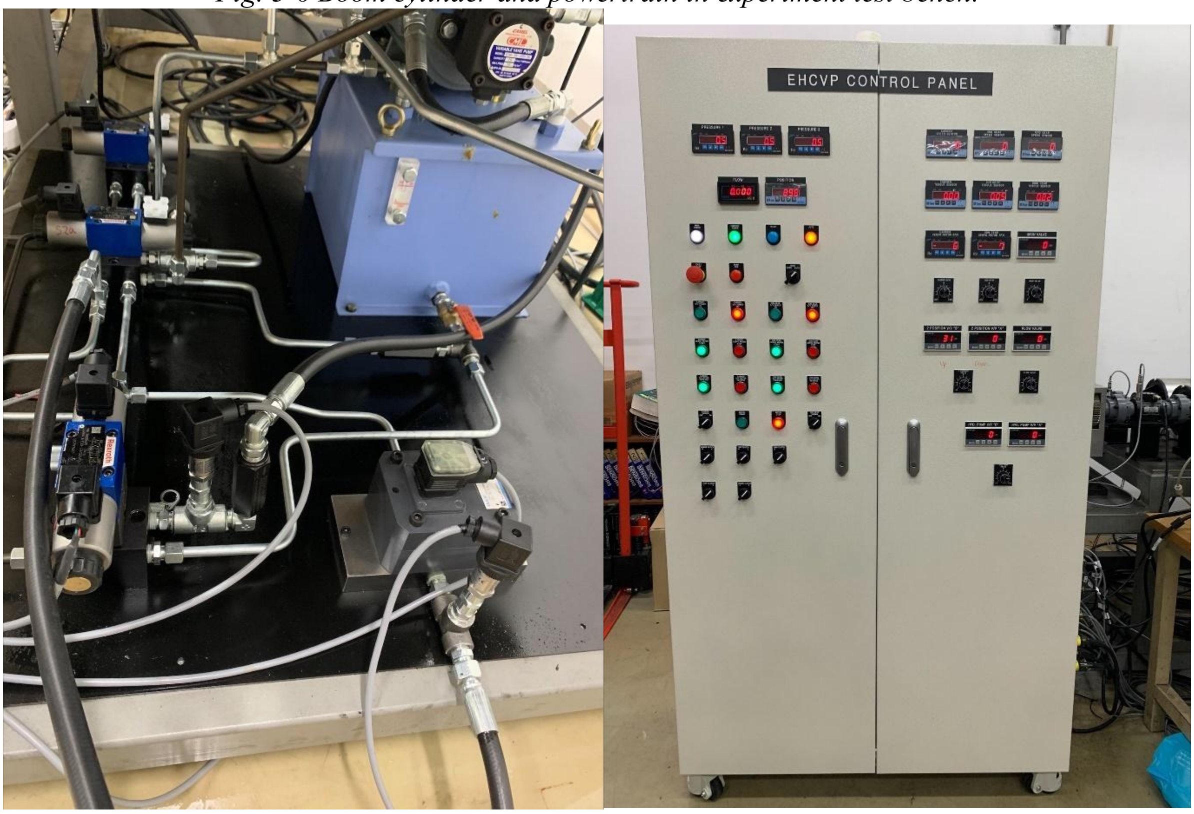


Fig. 3-7 Hydraulic system and control box in experiment test bench.

Table 3-1 comparison of 3 above configurations

Components	Parameters	Capacity	Unit
Cylinder	Piston diameter	50	[mm]
	Rod diameter	28	[mm]
	Length	0.75	[m]
	Max pressure	150	[bar]
Variable hydraulic pump	Maximum displacement	30	[cm^3/rev]
	Maximum pressure	250	[bar]
	Maximum speed	1500	[rpm]
Fixed hydraulic motor	Maximum displacement	10	[cm^3/rev]
	Maximum pressure	120	[bar]
	Maximum speed	1300	[rpm]
Electric motor/generator	Maximum power	5.5	[kW]
Electric motor	Maximum power	7.5	[kW]
Pulley	Diameter 1	130	[cm]
	Diameter 2	170	[cm]
Battery	Number of cells in series	6	[cell]
	Number of cells in parallel	1	[cell]
	Cell Voltage Limit	2.5 - 4.2	[V]

The detail parameters of the EHCVP system are presented in Table 3-1. In actual ICE, the speed ranges from approximately 800 rpm to 4000 rpm. When the speed of the engine is lower than 800 rpm, the engine cannot operate. Considering the small size of the test bench, the speed range of the ICE is reduced from 100 rpm to 500 rpm to demonstrate the trend of energy-saving efficiency. The real ICE in the excavator is controlled through the engine control unit (ECU), in which the control program is established. Based on the joystick signal, the ECU controls the ICE to drive the hydraulic pump. In the experiment, an industrial personal computer (IPC) is adopted, and the control program is implemented in Simulink to control the electric motor to drive the hydraulic pump. In terms of the hardware, the electric motor is used instead of the engine. In terms of the software, the IPC is used instead of the ECU. The comparison of the engine control in the real excavator and the experiment is shown in Fig. 3-8.

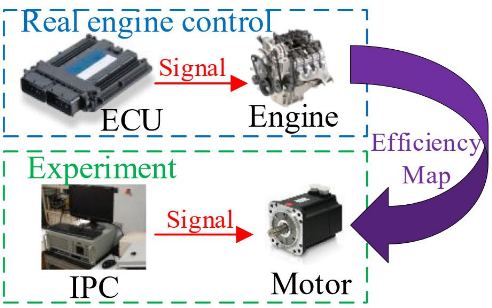


Fig. 3-8 Comparison of engine control in the real excavator and the experiment.

3.4. EHCVP model

3.4.1. Boom up process

During operation, the desired velocity of the boom cylinder can be decided by the joystick signal as.

$$v_{\mathrm{req}} = \alpha v_{\mathrm{max}} \tag{3.1}$$

where, α is the joystick signal with the positive and negative values are the boom up and down modes, respectively. v_{req} is the required velocity and v_{max} is the maximum velocity of the boom cylinder. From the required velocity, the flow rate of pump q_p can be calculated as.

$$q_p = v_{\mathrm{req}} A \tag{3.2}$$

where A denotes the area of the rod chamber. The power requirement of the main pump P_{req} can be estimated based on the required flow rate as

$$P_{\mathrm{req}} = p_p q_p \tag{3.3}$$

where p_p denotes the pressure at the output port of the main pump. Then, the torque of the main pump can be expressed as

$$T_p = \frac{p_p D_{\mathrm{P}}}{2\pi \eta_{\mathrm{Pm}}} \tag{3.4}$$

where, D_P is the displacement of the hydraulic pump, and η_{HPm} is the hydro-mechanical efficiency of the hydraulic pump which is a variable value depending on the pump's displacement and speed. The speed of the main pump can be calculated based on the pump displacement as

$$\omega_p = \frac{q_p}{D_{\mathrm{P}} \eta_{\mathrm{Pv}}} \tag{3.5}$$

where η_{Pv} denotes the volumetric efficiency of the hydraulic pump. The friction in the hydraulic pump is the reason for the loss in mechanical efficiency, and the leakage leads to a decrease in volumetric efficiency. The power sources are connected to the hydraulic system through the planetary gear. The speeds of carrier gear (ICE speed) and sun gear (electric motor/generator speed) can be calculated from the ring speed as

$$N_{\mathrm{s}} \omega_{\mathrm{s}} + N_{\mathrm{r}} \omega_{\mathrm{r}} = (N_{\mathrm{s}} + N_{\mathrm{r}}) \omega_{\mathrm{c}} \tag{3.6}$$

where, ω_c and ω_s denote the speed of carrier gear and sun gear, respectively. N_s and N_r express the number of teeth of the sun gear and ring gear. The torque of each gear can be expressed as

$$T_{\mathrm{r}} = T_{\mathrm{s}}\frac{N_{\mathrm{r}}}{N_{\mathrm{s}}} = T_{\mathrm{c}}\frac{N_{\mathrm{r}}}{N_{\mathrm{r}} + N_{\mathrm{s}}} \tag{3.7}$$

where, T_c and T_s are the torque of the carrier gear and sun gear, respectively. The power of the engine P_{eng} and the electric motor P_{motor} can be calculated as

$$P_{\mathrm{eng}} = \frac{\omega_{\mathrm{c}} T_c}{\eta_{eng}}$$
$$P_{\mathrm{motor}} = \begin{cases} \dfrac{\omega_{\mathrm{s}} T_{\mathrm{s}}}{\eta_{\mathrm{motor}}}, \omega_{\mathrm{s}} T_{\mathrm{s}} > 0 \\ \omega_{\mathrm{s}} T_{\mathrm{s}} \eta_{\mathrm{motor}}, \omega_{\mathrm{s}} T_{\mathrm{s}} \le 0 \end{cases} \tag{3.8}$$

where η_{eng} and η_{motor} denote the engine and the electric motor/generator efficiencies. From the Eqs. (3.3)(3.6), the relationship between the power requirement and the power sources can be calculated as

$$P_{req} = P_{eng} + P_{motor} \tag{3.9}$$

During the operation, the electric motor/generator can operate in two different functions with $P_{motor}>0$ means that it is working as a motor, and $P_{motor}<0$ means that it is in the generator mode. Therefore, a good selection in the working function of the electric motor/generator can not only meet power requirements but also improve the efficiency of the ICE. The energy consumption of the ICE and the electric motor/generator can be calculated as.

$$\mathrm{E}_{eng} = \int P_{eng} dt$$
$$\mathrm{E}_{\mathrm{motor}} = \int P_{motor} dt \tag{3.10}$$

The above analysis proved that the efficiencies of the ICE, electric motor/generator and hydraulic pump are the key factors to save energy during the moving up process. Optimizing these parameters can help the system achieve the highest effectiveness. Finally, the total energy consumption of the proposed EHCVP can be as

$$E_{\mathrm{total}} = E_{\mathrm{eng}} - E_{motor} \tag{3.11}$$

3.4.2. Boom down process

During the boom-lowering process, the boom cylinder can move without supplying power from the power sources. The potential hydraulic energy is converted to mechanical energy by the hydraulic motor. Then, the hydraulic energy at the inlet port can be estimated as.

$$E_h = \int \frac{P_{hm} Q_{hm}}{600} dt \tag{3.12}$$

where P_{hm} and Q_{hm} denote the pressure and flow rate at the inlet port of the hydraulic motor, respectively. The speed of the hydraulic motor ω_{hm} is calculated as.

$$\omega_{hm} = \frac{\eta_{hmv} Q_{hm}}{D} \tag{3.13}$$

where D is the displacement of the fixed hydraulic motor η_{hmv} and is the hydraulic motor's volumetric efficiency. The output mechanical energy E_m at the hydraulic motor can be calculated by

$$E_m = \int T_{hm} \omega_{hm} dt \tag{3.14}$$

where the actual torque at the output shaft of the fixed hydraulic motor T_{hm} is estimated as.

$$T_{hm} = \frac{\eta_{hmm} \Delta p D}{2\pi} \tag{3.15}$$

where η_{hmm} denotes the hydraulic motor's mechanical efficiency, Δp is the changed pressure between two ports of the fixed hydraulic motor. Subsequently, the mechanical energy is converted to electric energy through the generator and stored in the battery. From the torque and speed of the electric motor/generator, the generated energy E_{gen} can be expressed as

$$E_{gen} = \int \eta_{motor} T_r \omega_r dt \tag{3.16}$$

The overall regeneration efficiency of the EHCVP including mechanical and volumetric efficiency of the hydraulic motor and electric motor/generator efficiency can be estimated by

$$\eta_{tot} = \eta_{hmm} \eta_{hmv} \eta_{motor} \tag{3.17}$$

Eq. (3.17) indicates that the regeneration efficiency is dependent on the hydraulic motor and electric motor/generator efficiencies. Due to the fixed displacement hydraulic motor, controlling the speed of the electric motor/generator in the suitable range can enhance the amount of recovered energy.

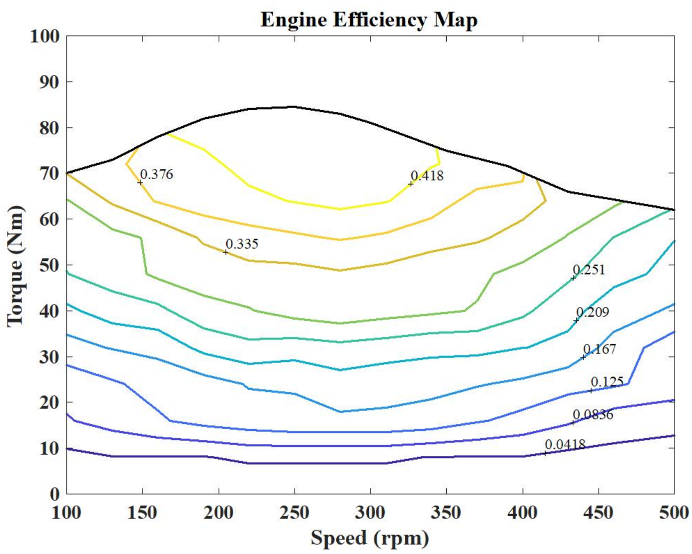


Fig. 3-9 Engine efficiency map.

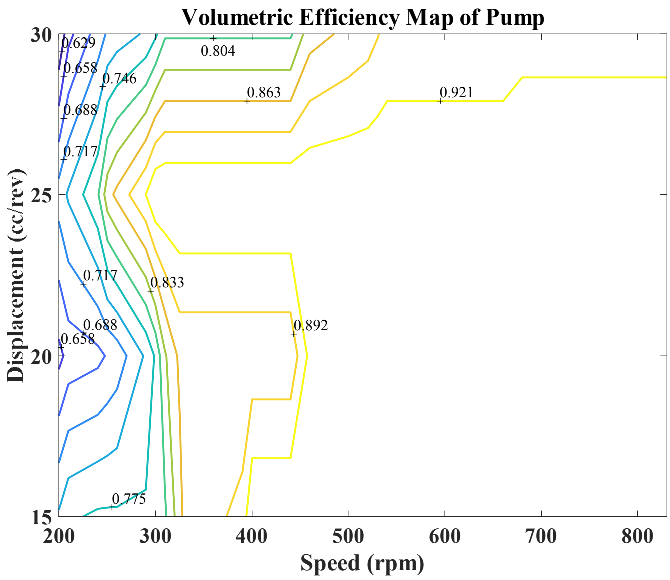


Fig. 3-10 Mechanical efficiency map of the pump at 20 bar.

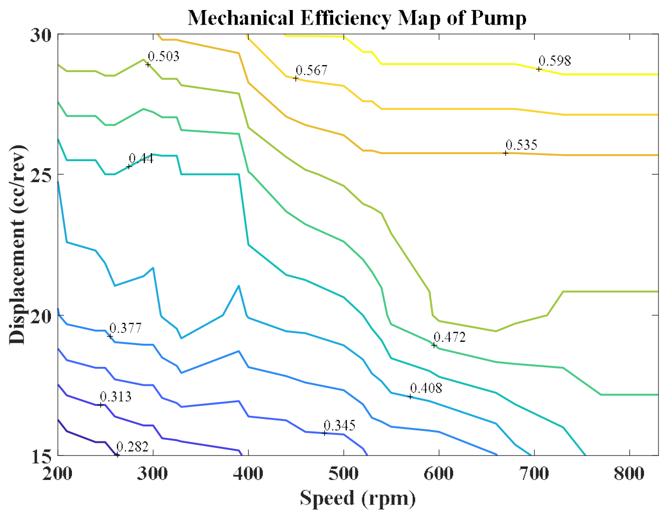


Fig. 3-11 Volume efficiency map of pump at 20 bar.

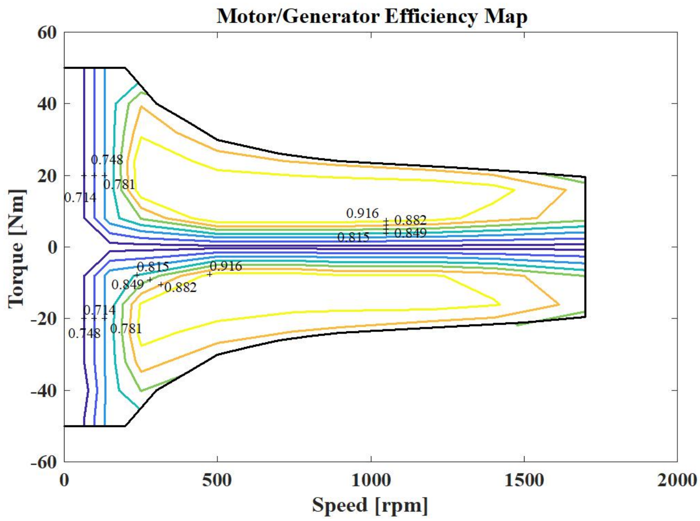


Fig. 3-12 Electric motor/generator efficiency map.

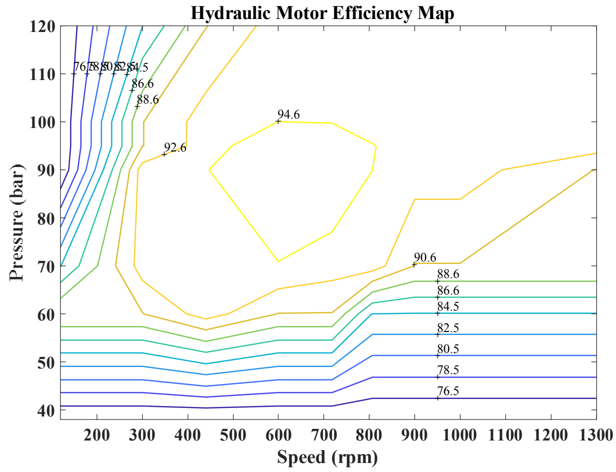


Fig. 3-13 Hydraulic motor efficiency map.

As the above analysis, the fuel economy and recovered energy can be enhanced by maintaining the devices in a high-efficiency area during operation. Considering the efficiency map of the ICE, the efficiency value is decided by the torque and speed as shown in Fig. 3-9. It can be seen that this value when increasing the torque of ICE can reach up to 43 %. Meanwhile, the efficiency value at the highest speed of the ICE is only 25.1%. Therefore, increasing the torque instead of increasing the speed of the ICE can help improve the efficiency with the same power requirement as calculated in Eq. (3.9). The high-performance area concentrating on the middle area of the map corresponds to the ICE working at 50% of the rated speed and torque between 60 and 80 Nm. Besides the efficiency of the ICE, the hydraulic pump efficiency is also a key factor to determine the overall efficiency of the proposed EHCVP. Eqs. (3.2)-(3.5) indicated that mechanical friction and oil leakage are the reasons that cause the variation of the mechanical efficiency and volumetric efficiency, respectively. These parameters are changed according to the displacement and speed of the hydraulic pump during the working process. The combination of these values forms the complete mechanical and volumetric efficiency maps as shown in Figs. 3-10, 3-11. The final factor affecting the performance of the proposed EHCVP during cylinder extraction is the electric motor/generator. The generator performance is shown in Fig. 3-12. Normally, the electric motor/generator can easily work with high performance. Therefore, the main function of the electric motor/generator in the system is to support the ICE during operation.

In the regeneration part, the recovery efficiency highly depends on the efficiency of the hydraulic motor due to the high performance of the electric motor/generator. Considering the hydraulic motor efficiency map in Fig. 3-13, it indicates that the high-efficiency area is concentrated in the central region of the map corresponding to the motor working at half-rated pressure and speed working condition. Hence, increasing the speed or pressure of the hydraulic motor can improve working efficiency. However, it is impossible to change the hydraulic motor's pressure since it is depended on the cylinder load. Meanwhile, the speed of the hydraulic motor can be increased through the gear ratio at the double-clutch (9). Therefore, choosing the suitable gear ratio can improve the efficiency of the hydraulic motor as well as the efficiency of energy regeneration. From the above analysis, an energy management strategy will be designed to maintain the EHCVP at peak performance under different working conditions.

3.4.3. Lithium-Ion battery model

Besides the efficiencies of the system's devices, the SOC of the battery is also an important factor in the design of the control strategy. During the operation process, the SOC of the battery should be limited to a defined range to supply the existing power to support the ICE or regenerate the energy from the boom cylinder. The SOC is obtained using the widely used coulomb counting method

$$SOC(k+1) = SOC(k) + \frac{T_s}{C_n} I(k) \tag{3.18}$$

where C_n denotes the battery nominal capacity, T_s denotes the sampling interval in seconds, and I is the current of the battery.

3.5. Experiment and analysis

3.5.1. Working performance of EHCVP

One experiment involving three cycles is conducted, in which the velocities of boom-up mode and boom-down mode are 0.13 m/s, 0.1 m/s, and 0.05 m/s respectively, and the load is 600 kg. A 0.02 kWh battery is emulated in the Simulink software. Based on the measured speed and torque of the motor/generator, the energy consumption of the battery is calculated in the experiment. The control program is implemented in the Simulink software to control the test bench.

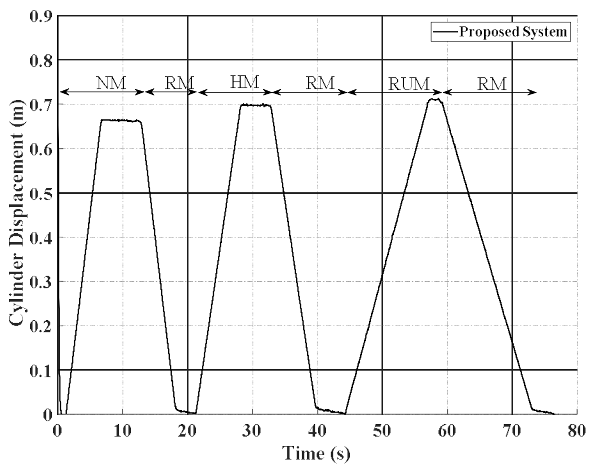


Fig. 3-14 Displacement of cylinder under three driving cycles (NM: normal mode, RM: regeneration mode, HM: hybrid mode, RUM, reuse mode).

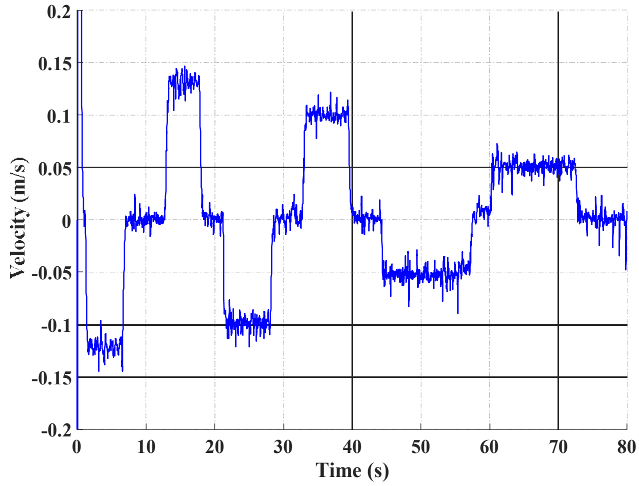


Fig. 3-15 Velocity of cylinder under three driving cycles

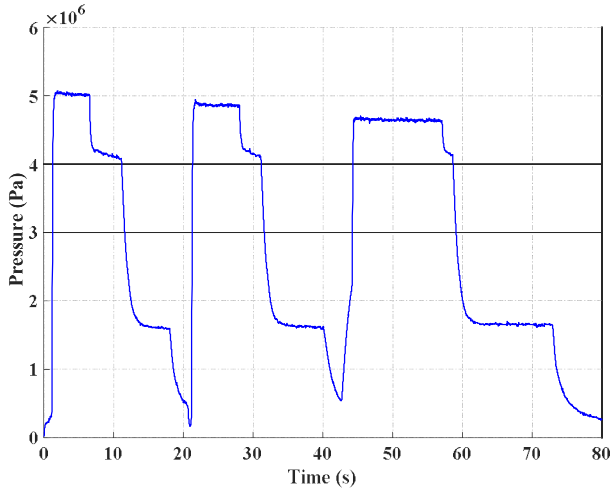


Fig. 3-16 Pressure of cylinder under three driving cycles

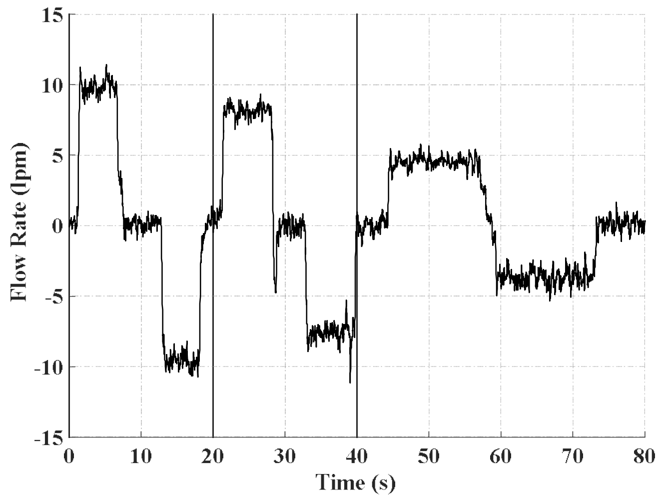


Fig. 3-17 Flow rate of the cylinder under three driving cycles

The displacement of load, pressure of the rod chamber, and hydraulic motor displacement are shown in Figs. 3-14 to 3-17, respectively. The speed of the carrier shaft (engine) and sun gear shaft (motor/generator) are shown in Fig. 3-18. The torque of the carrier shaft and sun gear shaft are shown in Fig. 3-19.

From 1 to 7 s, the system operates in the boom-up mode in cycle 1, in which only the engine drives the pump because the engine can operate in the high-efficiency range under this condition. Therefore, the motor/generator speed is zero. From 13 to 18s, the system operates in the boom-down mode in cycle 1, in which the hydraulic motor operates to regenerate the energy. Hence, the speed of the motor is a positive value, and the engine speed is zero.

From 21 to 28s, the system operates in the boom-up mode in cycle 2, in which the EHCVP system operates in the hybrid mode. The motor/generator serves as a generator to charge the battery. Hence, the engine speed can be increased to ensure that the engine can operate in the high-efficiency range. The engine working points in cycles 1 and 2 are indicated in Fig. 16 by using red star points. The engine working points are located in the high-efficiency range. Subsequently, the system operates in the boom-down mode of cycle 2 from 33 to 40 s. The energy consumption of the EHCVP system is presented in Fig. 3-20.

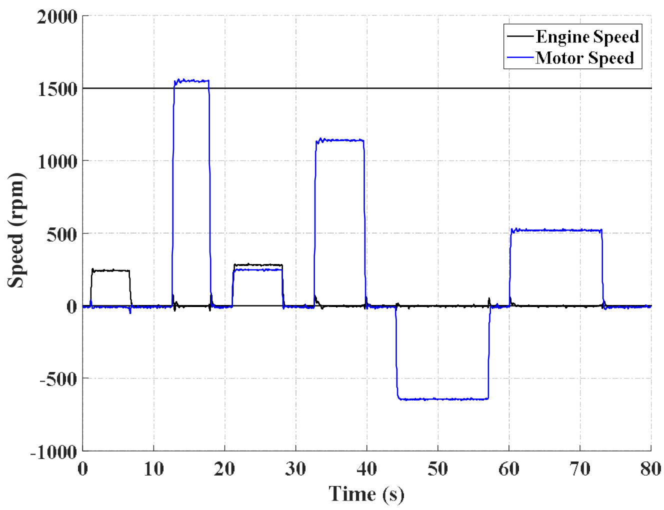


Fig. 3-18 Speed of ICE and electric motor/generator

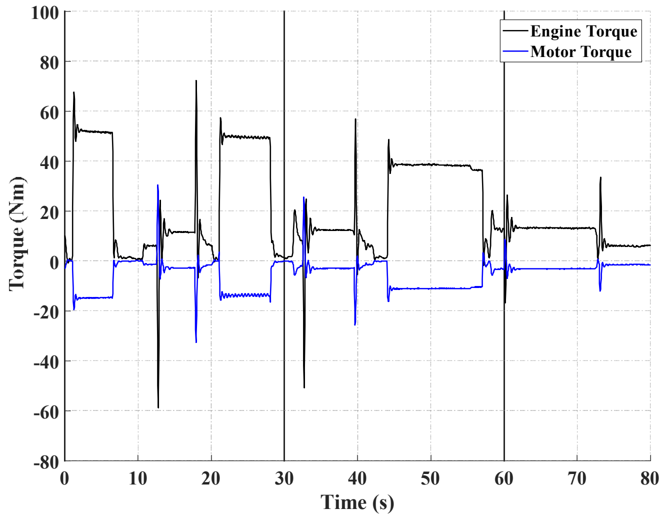


Fig. 3-19 Torque of ICE and electric motor/generator

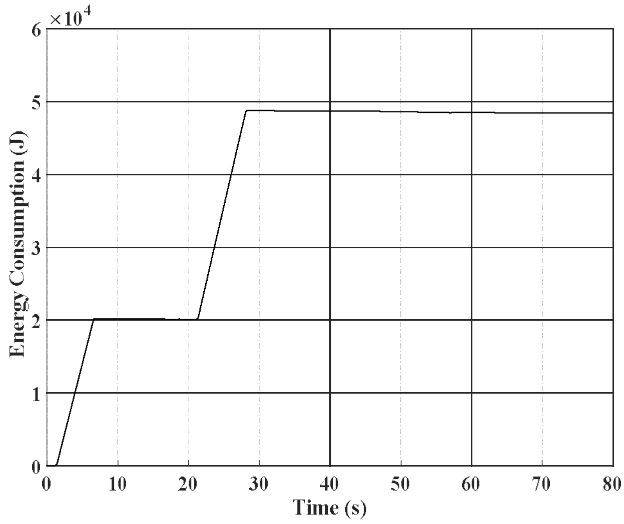


Fig. 3-20 Energy consumption of EHCVP system

From 44.2 to 57 s, the system operates in the boom-up mode in cycle 3, in which the system operates in the motor drive mode. Only the electric motor operates. In this condition, the required speed and torque of the hydraulic pump are low, and the SOC of the battery is relatively high. If the engine drives the pump, the engine working points do not lie in the high-efficiency range. Hence, the motor drive mode is selected.

Furthermore, an evaluation of the conventional system that does not include the EHCVP and energy regeneration system for 3 cycles is conducted. The experiment results are shown in Figs. 3-21 to 3-25. In the conventional mode, the displacement of the pump is fixed as 25 mL/r, and only the engine drives the system. The speed and torque of the engine are shown in Figs. 3-23 and 3-24, respectively. The energy consumption is shown in Fig. 3-25. Then, the comparison of energy consumption of both EHCVP and the conventional systems is listed in Table 3-2.

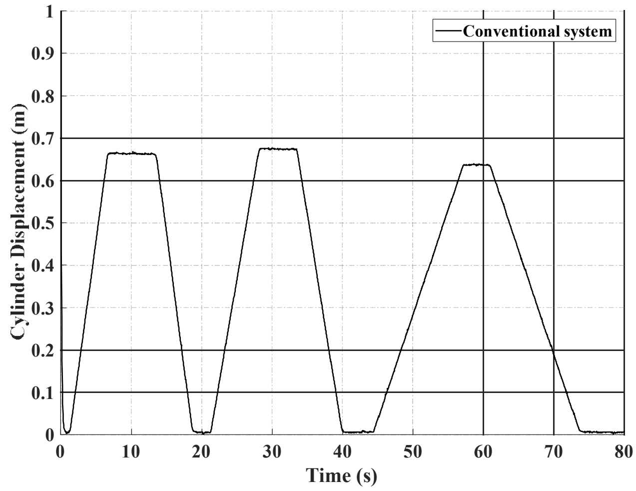


Fig. 3-21 Displacement of cylinder in conventional system

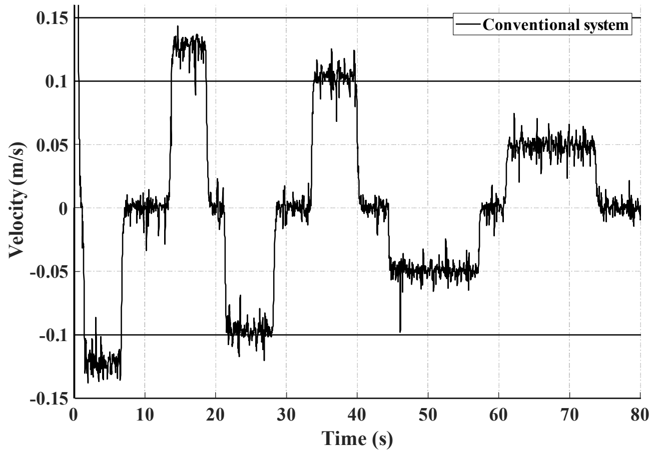


Fig. 3-22 Velocity of cylinder in conventional system

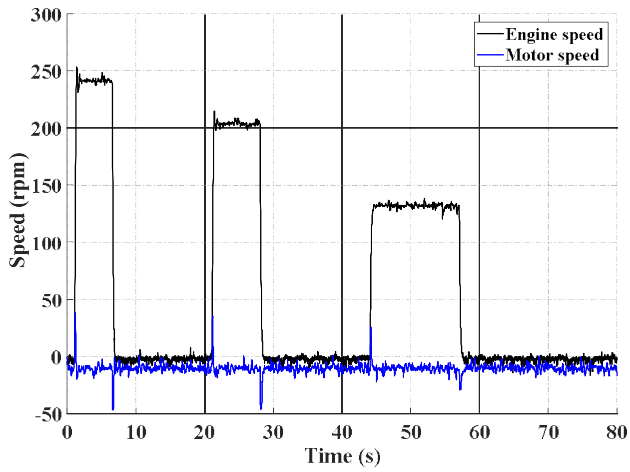


Fig. 3-23 Speed of ICE and electric motor/generator in conventional system

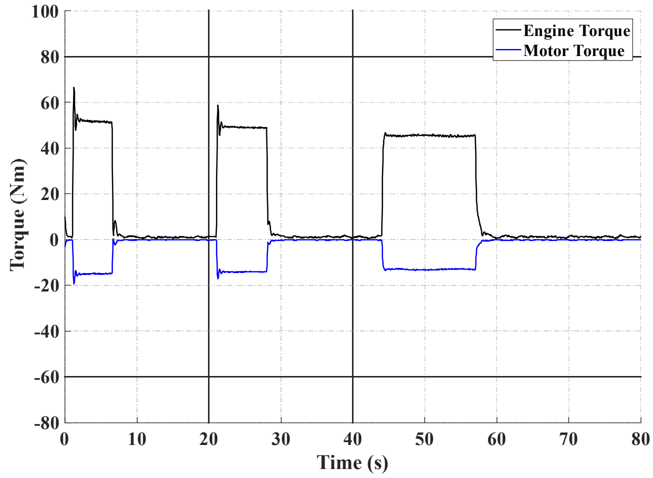


Fig. 3-24 Torque of ICE and electric motor/generator in conventional system

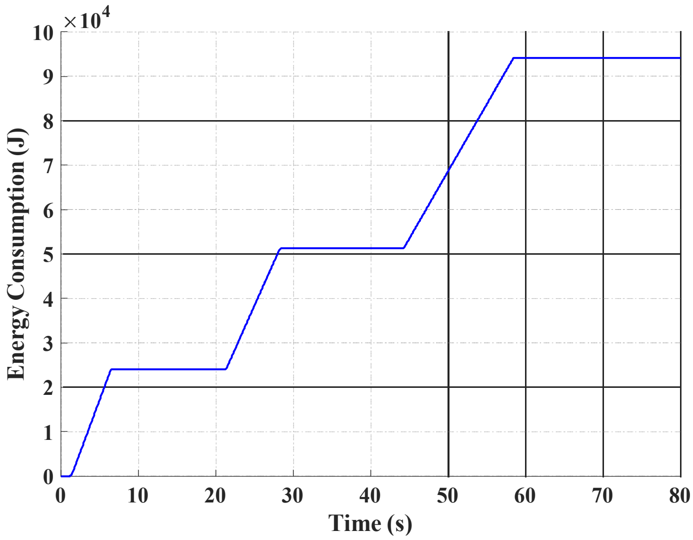


Fig. 3-25 Energy consumption of conventional system

Table 3-2 Energy consumption

System	E_{eng}	$E_{battery}$	E_{total}
Proposed system	48669 J	3450 J	52119 J
Conventional system	94168 J	0 J	94168 J

3.5.2. Energy saving efficiency in different conditions

The energy-saving efficiency under different loads is assessed. The average energy-saving efficiency and standard deviation pertaining to three experimental runs in different conditions are presented in Table 3-3.

Compared with the conventional system, the proposed system can save 36.69% to 45.16% of the energy under different conditions. Hence, the proposed system can save a significant amount of energy using the EHCVP and energy regeneration system.

Table 3-3 Results of energy saving efficiency

Load	Average energy saving efficiency	Standard deviation
200 kg	41.15%	0.48%
400 kg	36.69%	0.10%
600 kg	45.16%	0.20%

3.5.3. Economic analysis of proposed system

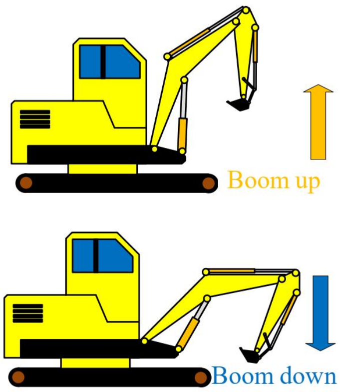


Fig. 3-26 Typical working cycle of boom in hydraulic excavator

The EHCVP is proposed for the hydraulic excavator, especially the boom system. In the real working condition of the excavator, the boom moves up and down repeatedly, which is shown in Fig. 3-26. To test the economic results of the hydraulic excavator boom system, a typical working condition of the boom is selected, in which the boom moves up and down for 6 cycles with 180 s. The load is set to 600 kg, and the velocity of the cylinder is 0.1m/s, which is a typical velocity of a boom cylinder for a real excavator. The energy consumption is measured and converted to the fuel consumption of diesel. To verify the energy saving of the proposed system, the conventional system is also tested without EHCVP and an energy regeneration system.

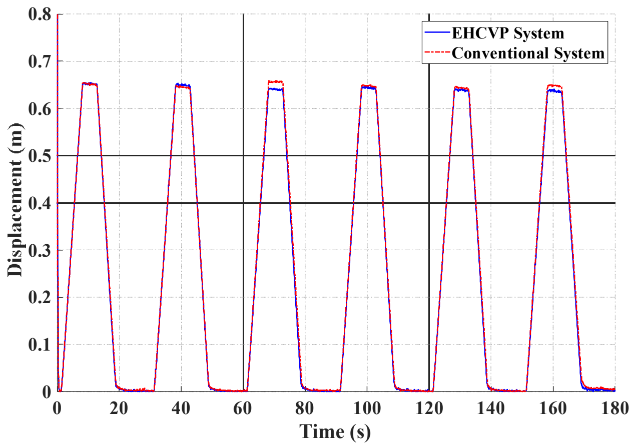


Fig. 3-27 Cylinder displacement of both EHCVP and conventional systems

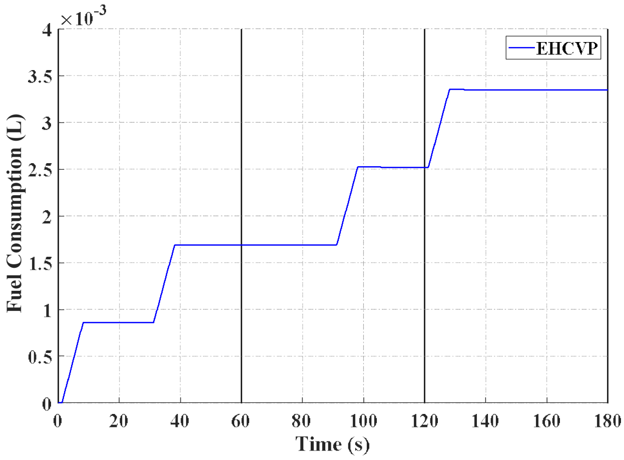


Fig. 3-28 Fuel consumption of EHCVP system

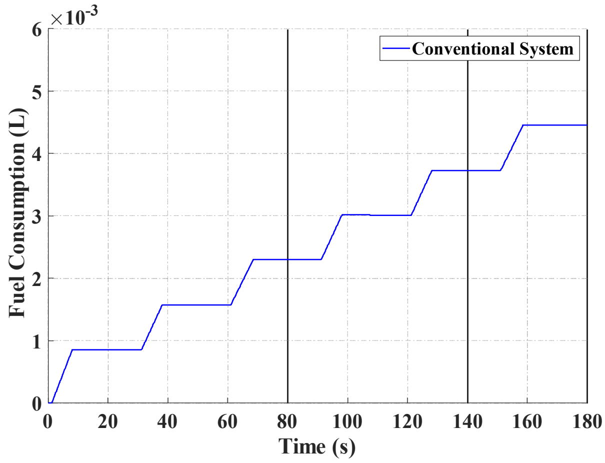


Fig. 3-29 Fuel consumption of conventional system

The cylinder displacements of the proposed system and conventional system are shown in Fig. 3-27. In our research, one liter of diesel fuel has an energy content of appropriately 38 MJ which appropriates to 10 kWh. Besides, diesel produces 2.63 kg of CO_2 per liter of the diesel vehicle. Therefore, the fuel consumption of the proposed system and conventional system are 0.0030 L and 0.0043 L in Fig. 3-28 and 3-29. Taking a 48-t excavator as an example, the 48-t excavator is 160 times larger than the testbench. Then, according to the 6 cycles of 180 s, working hours of 10 h per day, the total fuel saving is 41.6 L per day of a 48-t excavator. According to the calculation of 250 days per year [6], the annual fuel consumption can be reduced by 10400 L. Based on the carbon dioxide production of diesel, the carbon dioxide emission can be reduced by 27352 kg per year. Hence, the proposed system can reduce fuel consumption and carbon dioxide emission effectively.

According to a report by Off-Highway Research, hydraulic excavators reached 3.8 million units globally in 2017. In 2020, Chinese sales volume of hydraulic excavators was 320 thousand, which increased by 39% compared to 2019. Furthermore, the proposed EHCVP can be used in other construction machines, such as a forklift. Hence, the application of the proposed system in real excavators and other construction machines has a large potential to reduce fuel consumption and emission globally.

3.6. Chapter summary

An innovative hydraulic hybrid excavator with an EHCVP was developed in this chapter. In conventional systems, the speed and torque of the ICE are decided by the flow requirement and load. However, in the proposed EHCVP, both the speed and torque of the ICE were controlled to be in the high-efficiency range. Hence, the energy consumption of the ICE can be reduced. The experiment results demonstrated that when the EHCVP was adopted, the ICE working points were located in the high-efficiency range, and the energy-saving efficiency ranged from 36.69% to 45.16%. With the increasing sales volume of hydraulic excavators globally, the application of the proposed system in excavators can reduce fuel consumption and emission effectively.

The proposed hybrid hydraulic excavator with EHCVP can reduce energy consumption. However, this research still involves certain limitations. If the hydraulic excavator operates under an extremely large load and medium velocity, the engine working points may be located in the high-efficiency range even without using the EHCVP. In this specific condition, the EHCVP cannot control the engine to work with higher efficiency, and only the energy regeneration part can help reduce energy consumption. Hence, the next chapter will present a modification for enhancing energy-saving efficiency under all conditions.

Chapter 4
IMPROVEMENT OF ENERGY SAVING

4.1. Introduction

To save energy, the EHCVP was proposed as a powertrain for a hydraulic excavator in the previous chapter. The ICE and electric motor/generator not only can drive the main pump separately but also can drive the main pump together as shown in Fig. 4-1. In EHCVP, the electric motor/generator can work as a motor or a generator to provide mechanical energy or generate electric energy. The speed of the ICE and motor/generator decide the speed of the main pump through planetary gear. Then the ICE speed can be controlled to its high-efficiency range with EHCVP. A variable displacement pump was installed in the system to govern the torque of the ICE. Hence, the ICE working points can be controlled in its high-efficiency range. However, the maximum displacement of the hydraulic pump limits the controlled range of ICE torque. If a larger hydraulic pump is selected in the system, the efficiency can be improved in the condition of large velocity. But the hydraulic pump will always work with a low and middle displacement, which leads to low efficiency of the hydraulic pump in other conditions. Finally, the fuel consumption of the total system cannot be improved with varying velocities in real engineering. Hence, the current structure of EHCVP limits the improvement of energy-saving efficiency.

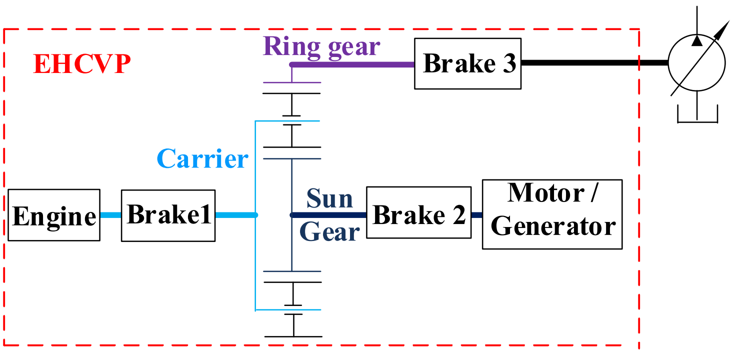


Fig. 4-1 Structure of the EHCVP I

To enhance the energy-saving efficiency, an innovative EHCVP is proposed as shown in Fig. 4-2. A two-speed gearbox is installed between the ring gear shaft and the hydraulic pump. The ICE torque is governed by the hydraulic pump and gearbox mainly. So, the working range of engine torque can be controlled more flexibly than that of the current EHCVP. Meanwhile, the electric motor/generator governs the speed of ICE. Hence, the engine working points can be controlled in the high-efficiency range. The proposed EHCVP of this chapter is named EHCVP II.

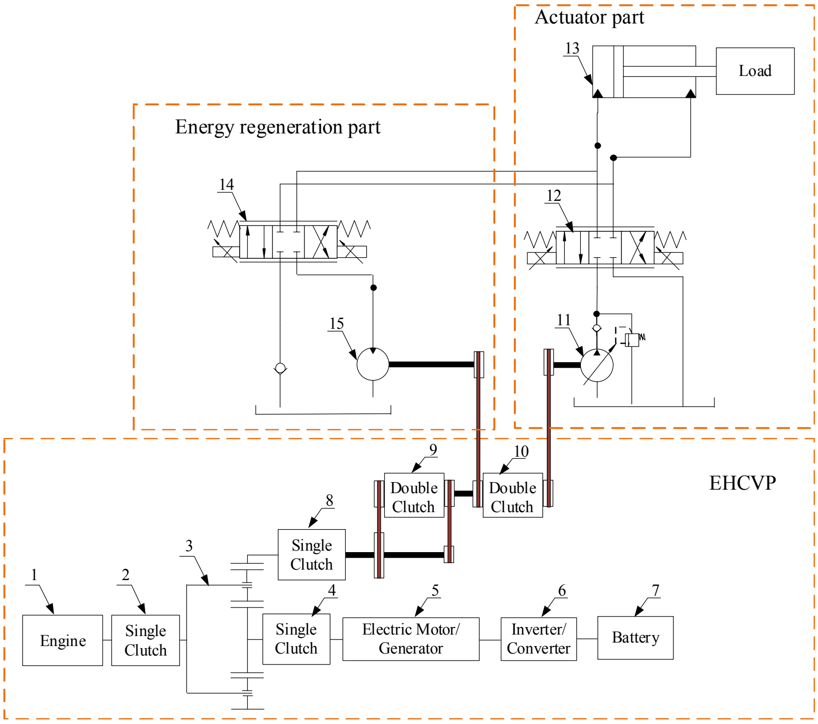


Fig. 4-2 Structure of the proposed boom system with EHCVP II

4.2. Working principle

The overall structure of the proposed EHCVP is presented in Fig. 1. The ICE and the electric motor/generator are the main power sources supplying power for the system through a planetary gear in which the engine, the electric motor/generator, and the hydraulic devices are connected with carrier gear, sun gear, and ring gear, respectively. The speeds of carrier gear (ICE speed) and sun gear (electric motor/generator speed) can be calculated from the ring speed as

$$N_s\omega_s + N_r\omega_r = (N_s + N_r)\omega_c \tag{4.1}$$

where, ωc, ωr, and ωs denote the speeds of the carrier, ring, and sun gears, respectively. Ns and Nr express the number of teeth of the sun gear and ring gear. The torque of each gear can be expressed as

$$T_r = T_s\frac{N_r}{N_s} = T_c\frac{N_r}{N_r + N_s} \tag{4.2}$$

where, Tc, Tr, and Ts are torques of the carrier, ring, and sun gears, respectively. Two double clutches with different functions are integrated at the output shaft of the ring gear where the double-clutch 1 is used to adjust the gear ratio R and the other one is used to switch the connection between the EHCVP with the hydraulic pump or hydraulic motor.

$$R = \frac{D_{ri}}{D_{di}} \tag{4.3}$$

where Dri and Ddi are the diameters of the pulley at the double clutch 1 with the values of gear ratios 1 and 2 are 1.3 and 1, respectively. The speed of the hydraulic pump ω_r is expressed as

$$\omega_p = \omega_r R \tag{4.4}$$

The torque of the hydraulic pump T_p is expressed as

$$T_p = \frac{T_r}{R} \tag{4.5}$$

In the actuator part, driven by this EHCVP, the variable displacement pump supplies hydraulic flow to the boom cylinder with the flow's direction can be decided by the spool position of the proportional directional valve. In the regeneration part, a hydraulic motor is installed at the bore chamber line. The combination of a hydraulic motor, electric motor/generator, and battery inverter helps convert hydraulic energy into electrical energy. The generated energy E_{gen} can be expressed as

$$E_{gen} = \int \eta_{tot} T_r \omega_r dt \tag{4.6}$$

The overall regeneration efficiency η_{tot} of the EHCVP including mechanical η_{hmv} and volumetric efficiency η_{hmm} of the hydraulic motor and electric motor/generator efficiency η_{motor} can be estimated as

$$\eta_{tot} = \eta_{hmm} \eta_{hmv} \eta_{motor} \tag{4.7}$$

It indicates that the regeneration efficiency is dependent on the hydraulic motor and electric motor/generator efficiencies. Due to the fixed displacement hydraulic motor, controlling the speed of the electric motor/generator in the suitable range can enhance the amount of recovered energy. Based on the above structure, the proposed system can operate with four modes: normal mode, hybrid mode, reuse mode, and regeneration mode.

Normal mode: the main pump is driven by the ICE without support from the electric motor/generator. This mode is similar to the conventional HE. However, without switching the gear ratio, the working point of the ICE cannot adjust to improve its efficiency. Therefore, by integrating the double-clutch 1, the torque and speed of the ICE can be changed to achieve higher efficiency with the same power requirement.

Hybrid mode: the ICE and electric motor/generator drive the main pump together. The speed of the ICE can be adjusted by changing the speed of the electric motor/generator. Meanwhile, the torque of the ICE is decided by the load condition. Considering the conventional system, the gear ratio between the output shaft of the ring gear and the main pump was fixed. Therefore, the torque and speed of the main pump are similar to the torque and speed at the ring gear. In the case of low load condition of the boom cylinder, the efficiency of the ICE cannot improve by simply changing the speed of the ICE as in the conventional EHCVP which the double-clutch 1 is not integrated [86]. Therefore, in the proposed EHCVP system, by switching the double-clutch 1 to the gear ratio 1, not only the speed but also the torque of the ICE can be adjusted in the same working condition. Then, the efficiency of the ICE can easily achieve a higher value.

Reuse mode: the stored energy in the battery is supplied to the electric motor/generator working in the motor function. The electric energy is converted to mechanical energy and drives the main pump.

Regeneration mode: this mode is used for the boom-lowering process. The potential hydraulic energy in the bore chamber is captured and stored in the battery through the hydraulic motor and electric motor/generator working in the generator mode. In this case, the hydraulic motor can work with higher efficiency by increasing its pressure and speed. However, the pressure decided by the load condition cannot increase. So, to increase the speed of the hydraulic motor, gear ratio 1 is used.

4.3. Modification of experiment test bench

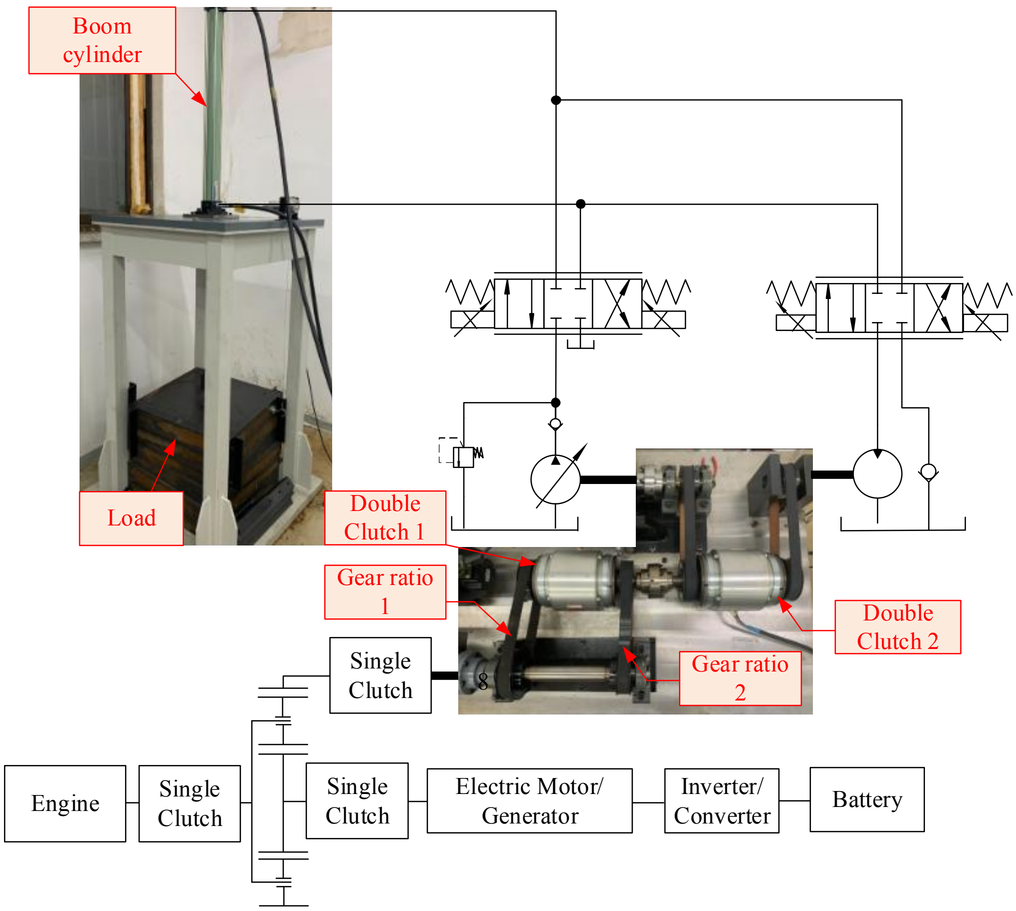


Fig. 4-3 Modification of the experiment test bench

Based on the above analysis, the ICE speed and toque are decoupled from the pump speed and torque, and energy regeneration can also be achieved to reduce the fuel consumption of the hydraulic excavator with EHCVP Ⅱ. To verify the energy saving of the proposed system, the test bench is built in the laboratory, as shown in Fig. 4-3. A cylinder is set up in a test bench to emulate the boom cylinder of an excavator, and the load is connected to the rod of the cylinder. Electric motor 1 and electric motor

2 emulate the ICE and motor/generator, respectively. The dual-clutch 1 is used as the gearbox, which has two gear ratios. The dual-clutch 2 controls the output shaft of dual-clutch 1 to be connected to the main pump or the hydraulic motor. If dual clutch 2 connects the output shaft of dual clutch 1 to the main pump, the system will work in boom-up mode. In boom-up mode, the main valve works at the left position, and the EHCVP Ⅱ drives the main pump to move the load up. If dual clutch 2 connects the output shaft of dual clutch 1 to the hydraulic motor, the system will work in boom-down mode. In boom-down mode, the energy regeneration valve V1 is open, and the fluid from the cylinder will flow to the hydraulic motor, which is connected to the EHCVP Ⅱ. The electric motor/generator 2 works as a generator to balance the torque of the hydraulic motor and to regenerate energy. The speed sensors and torque sensors are installed in each shaft of the planetary gear. A pressure sensor is installed in the output port of the rod chamber of the cylinder.

4.4. Energy management strategy

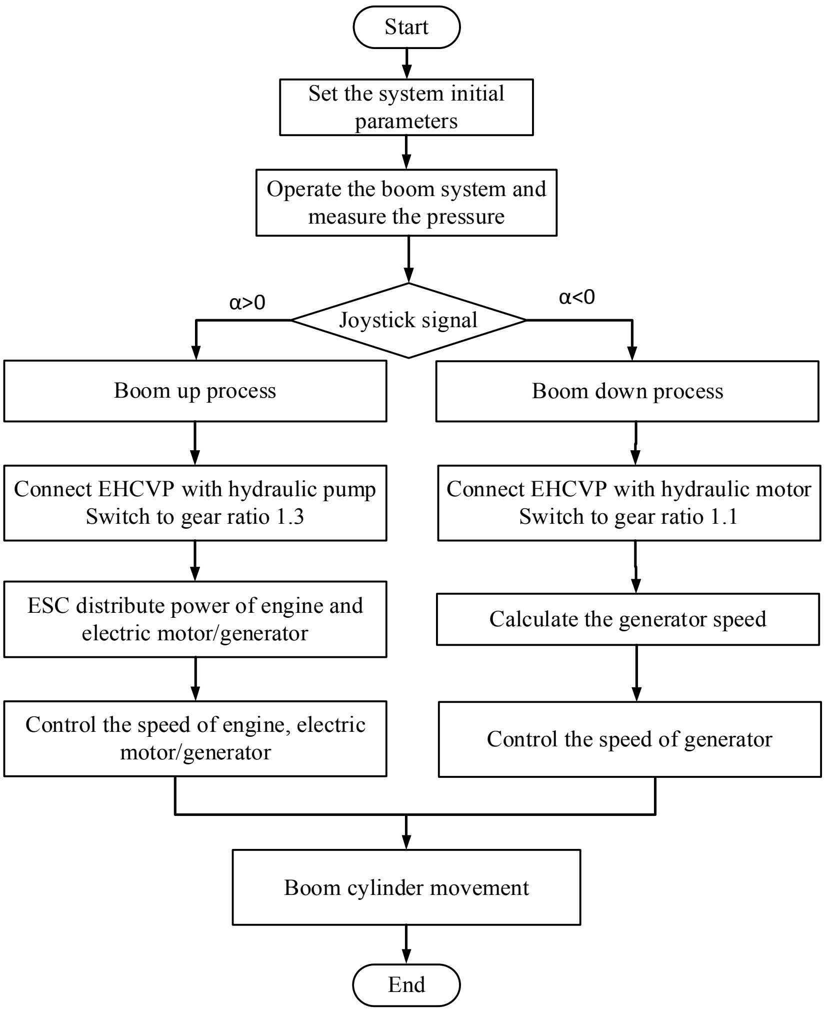


Fig. 4-4 Proposed energy management strategy

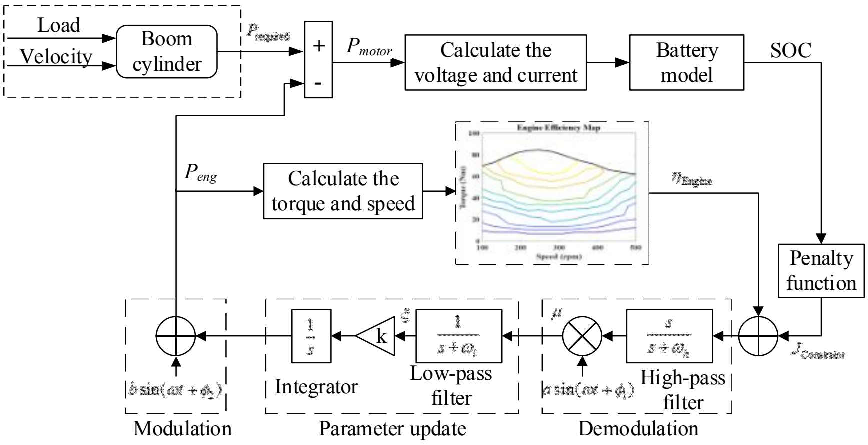


Fig. 4-5 Proposed extremum seeking based energy management strategy for EHCVP system

To manage the energy usage inside the EHCVP system effectively, the required power must be distributed efficiently between the engine and the electric motor/generator. On the other hand, concerning the complexity of the target system, it might be impossible to capture its dynamics just by mathematical modeling, which is required by various energy management schemes. Hence, a model-free, real-time energy management strategy would be a more suitable candidate for this system. Based on this observation, we employ the extremum seeking (ES) algorithm to optimize the energy flows of the system in this section. The structure of the proposed ES-based energy management strategy is presented in Fig. 4-4.

The ES is employed such that it could automatically alter the engine power P_{eng}, which accounts for a large proportion of the power demand P_{motor}. Consequently, the electric motor/generator provides for the residual energy requirement P_{motor}, which is obtained by subtracting the engine power from the power demand. Moreover, the proposed energy management strategy ensures that the engine would always operate in its high-efficiency region and that the battery state-of-charge (SOC) is maintained in the desired range. To meet this requirement on battery SOC, a penalty function is formulated below.

$$J_{\text{Constraint}} = -\left[K \cdot \max\left\{ \frac{SOC_{\min} - SOC}{SOC_{\min}}, 0, \frac{SOC - SOC_{\max}}{SOC_{\max}} \right\} \right]^2 \tag{4.8}$$

where K denotes the penalty gain, $SOC_{\min}$ and $SOC_{\max}$ represent the design SOC boundaries.

It is noted here that not the penalty function (15) but rather the engine efficiency is the objective that the proposed ES tries to maximize. Thus, $J_{\text{Constraint}}$ can be interpreted as a virtual disturbance that opposes the engine efficiency in value. As a result, the selection of the design parameter K demonstrates a trade-off between engine efficiency and battery usage. A large value K would prevent the battery unit from overcharging or over-discharging, whereas a small value would result in higher engine efficiency.

The mathematical equation set of the proposed energy management strategy is given, based on Fig. 4-5, as

$$\begin{cases} \mu = a\sin(\omega t + \phi_1) \cdot \left[\left(J_{\text{Constraint}} + \eta_{\text{eng}} \right) \cdot L^{-1}\left(\dfrac{s}{s+\omega_h} \right) \right] \\ \xi = \mu \cdot L^{-1}\left(\dfrac{1}{s+\omega_l} \right) \\ P_{\text{eng}} = b\sin(\omega t + \phi_2) + \xi \cdot L^{-1}\left(\dfrac{k}{s} \right) \\ P_{motor} = P_{\text{required}} - P_{eng} \end{cases} \tag{4.9}$$

where L^{-1} represents the inverse Laplace transform, and the notation " · " denotes the convolution operation.

The working cycle of the ES for the EHCVP system can be expressed as follows. First, the engine efficiency η_{Engine} and the penalty function $J_{\text{Constraint}}$ are calculated and added together before being injected into the demodulation process where they are multiplied by a sinusoid sharing the same frequency as the modulation signal. This stage might include an optional high-pass filter to remove bias from the input. In the following process, the demodulated signal is integrated to update the engine power value. This stage also might include a low-pass filter to remove high-frequency noise from the demodulated signal. The learning rate k can be tuned manually for fast response and higher accuracy. Next, the integrated signal is perturbed by a low-amplitude sinusoid in the modulation process before entering the EHCVP system as the new engine power demand.

4.5. Simulation results and discussions

4.5.1. Working performance of modified EHCVP

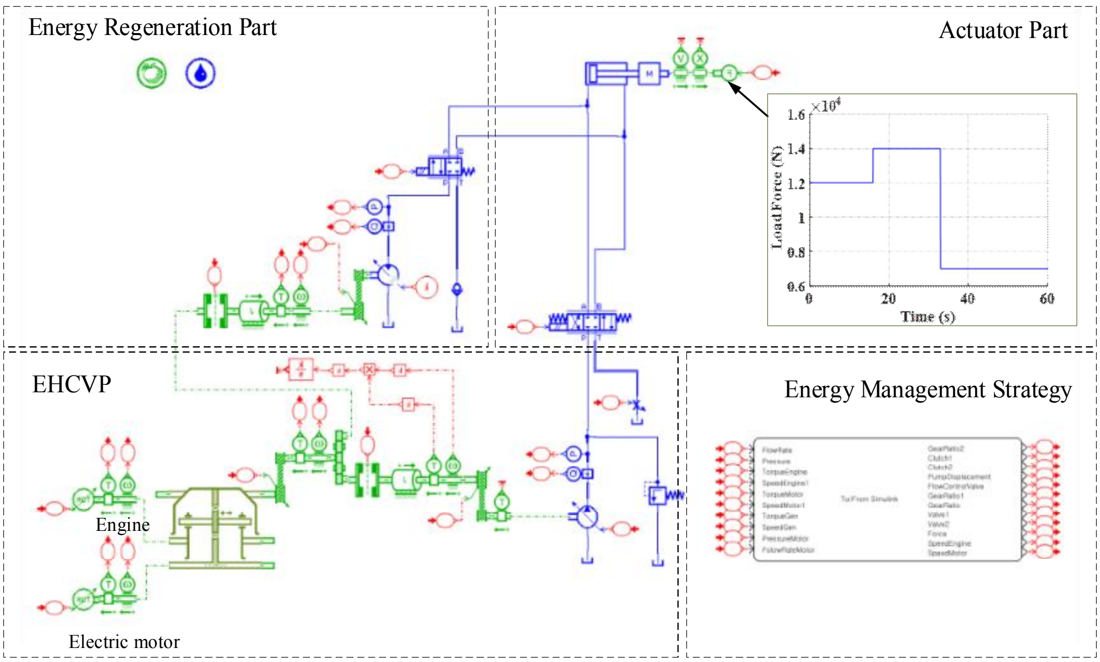


Fig. 4-6 Simulation model in AMESim software

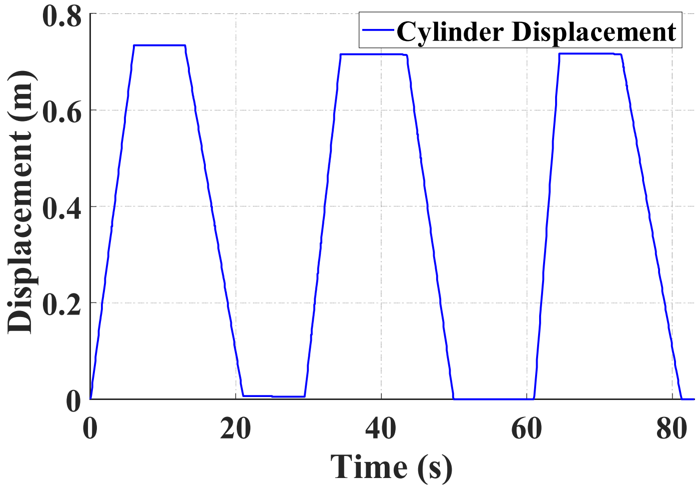


Fig. 4-7 Cylinder displacement during the operation

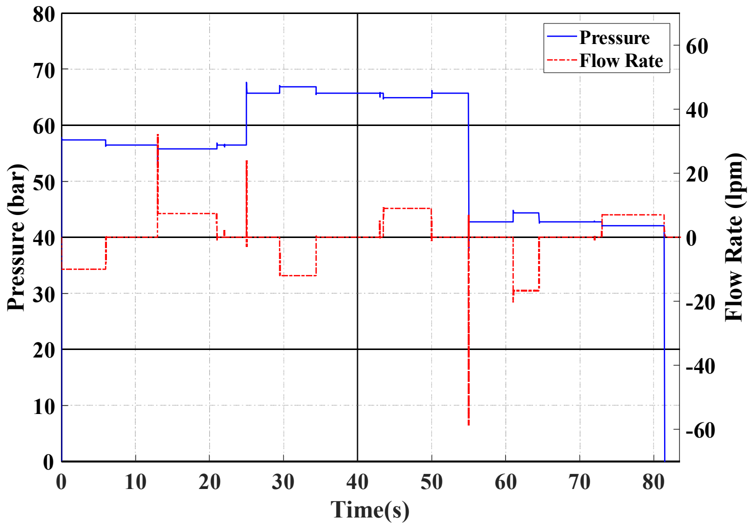


Fig. 4-8 Pressure and flow rate of the boom cylinder

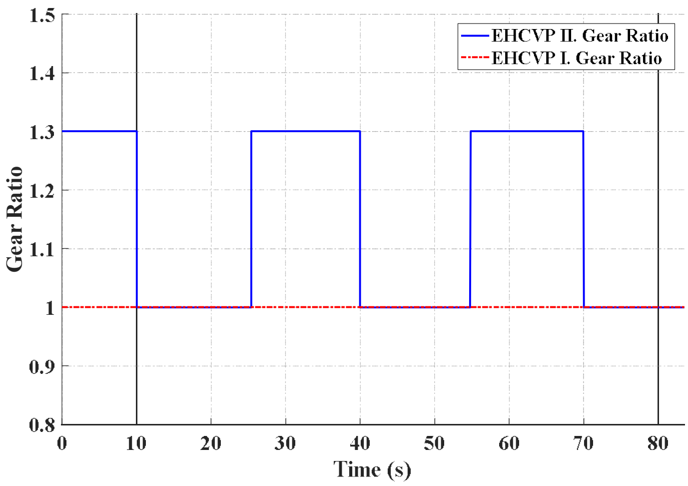


Fig. 4-9 Switching gear ratio

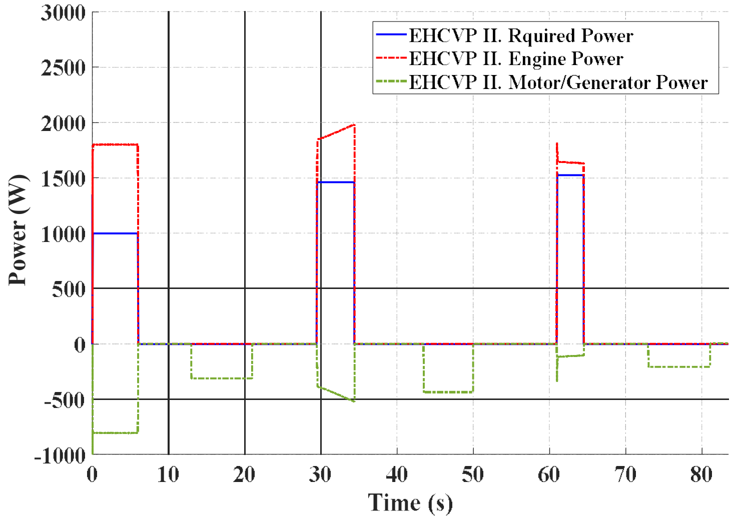


Fig. 4-10 Power distribution in EHCVP II

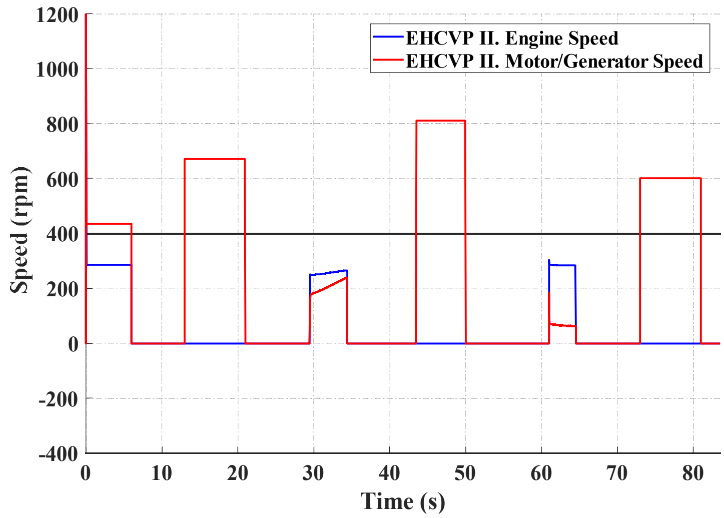


Fig. 4-11 Speed of the ICE and electric motor/generator in EHCVP II

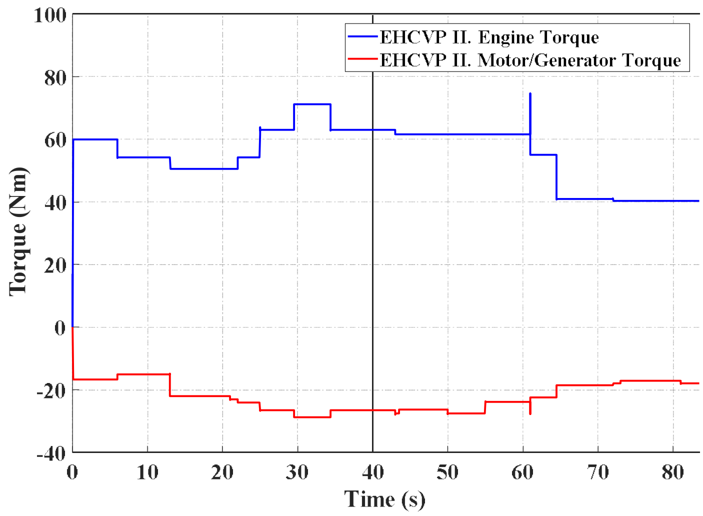


Fig. 4-12 Torque of the ICE and electric motor/generator in EHCVP II

To fully investigate the system performance and evaluate the effectiveness of the proposed energy management strategy-based ESC, an EHCVP simulation model is constructed by using a co-simulation between the AMESim software version 2020.1 and Matlab/Simulink 2017a as shown in Fig. 4-6. The simulation results of the proposed EHCVP are presented in Figs. 4-7 to 4-12. By using the energy management strategy-based ESC, the power requirement is distributed to the ICE and the electric motor/generator. During the lifting process of the boom cylinder in the first 2 cycles, the powers of the ICE at the high-efficiency points are higher than the power requirements. Hence, the excess power from the ICE is charged to the electric motor/generator and stored in the battery. With the final cycle, the power requirement is higher than the power of ICE at the high-efficiency point. In order to keep the ICE operating continuously in the high-efficiency region, the electric motor/generator is switched to the motor mode to compensate for the lack of power which is supplied by the battery. The torque and speed of the power sources are shown in Figs 4-11 and 4-12. As can be seen, the torque and speed values have opposite signs when the electric motor/generator operates in generator mode and vice versa for motor mode. Meanwhile, the ICE obviously supplies power to the boom system, so the values of the torque and speed are always the same signs. The torque and speed of the ICE are 81 Nm and 252 rpm, respectively.

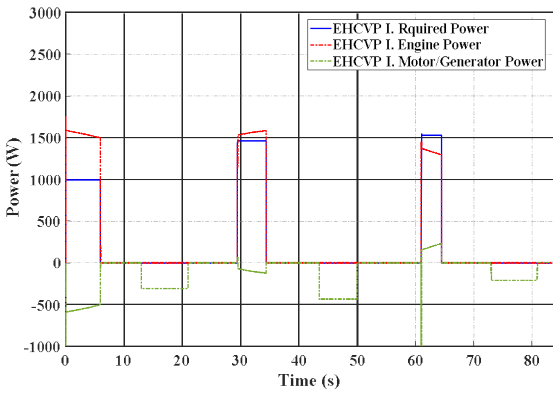


Fig. 4-13 Power distribution in conventional EHCVP I

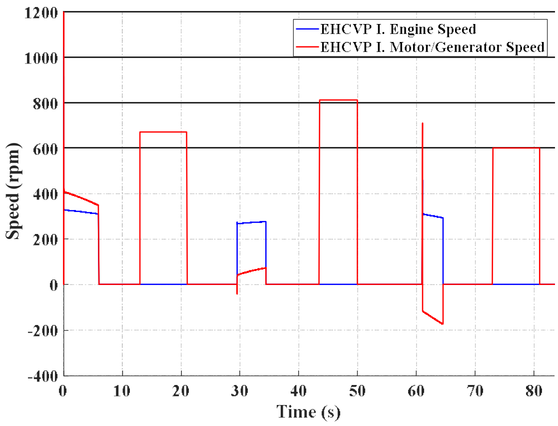


Fig. 4-14 Speed of the ICE and electric motor/generator in conventional EHCVP I

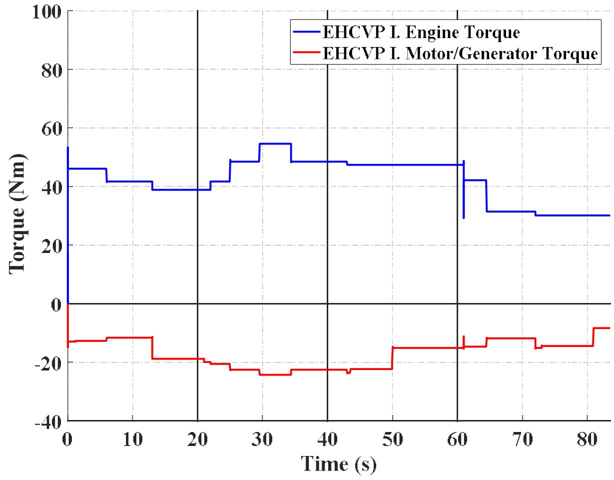


Fig. 4-15 Torque of the ICE and electric motor/generator in conventional EHCVP I

Figs. 4-13 to 4-15 show the simulation results of the conventional EHCVP. Similar to the proposed system, the powers of the ICE and the electric motor/generator of the conventional system are also calculated and distributed by the ESC. The electric motor/generator is also operated as the proposed system with the first 2 cycles using generator mode and the last cycle using motor mode. However, the difference here is that the engine torque cannot be increased to a higher value because the gear ratio remains constant. This reason leads to the engine's working efficiency of the conventional system being lower than the proposed system as shown in Fig. 4-16. From the torque and speed of the electric motor/generator and the pressure and flow rate of the boom cylinder, the energy regeneration efficiency can be calculated and reached up to 48.2 %.

The SOC of the battery in the conventional and proposed EHCVP is presented in Fig. 4-17. It can be seen that, with the same amount of required energy, for the ICE to operate in the higher efficiency region means that the ICE consumes more energy, and that excess energy will be charged into the battery through the electric motor/generator. Hence, the SOC of the battery in the proposed EHCVP is higher than the conventional one. Besides, thanks to working at higher efficiency of the ICE and charging more energy into the battery, even though the power consumption of the ICE in the proposed EHCVP is higher, its total energy consumption is still lower than the conventional system. Table 4-1 indicated that the energy saving of the new EHCVP can reduce by about 7% compared with the previous system.

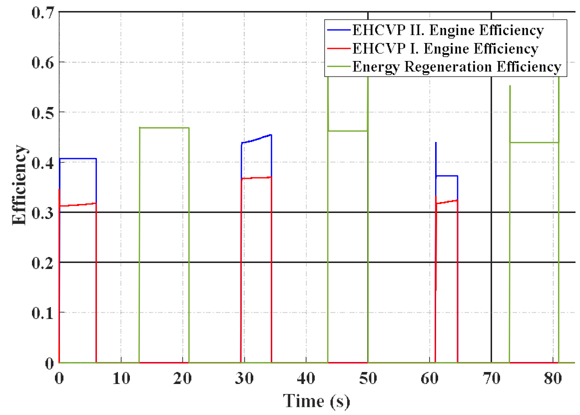


Fig. 4-16 Efficiency comparation

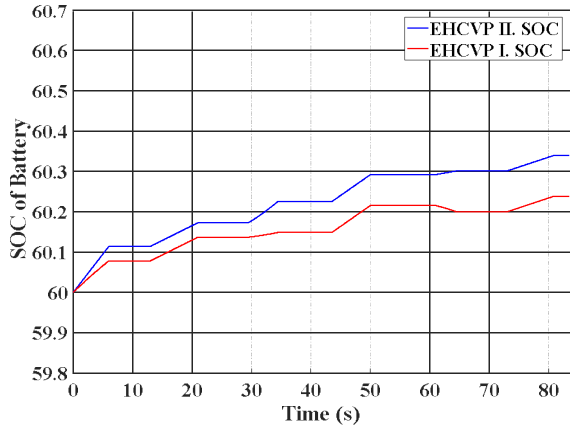


Fig. 4-17 SOC of battery.

Table 4-1 Total energy consumption and energy saving

Powertrain		**Proposed EHCVP**	**Conventional EHCVP**
Energy Comsumption	Engine	72.17 kJ	71.22 kJ
	Electric motor/generator	8.41 kJ	3.5 kJ
	Total	63.76 kJ	67.72 kJ
Energy Saving		5.86%	

4.5.2. Extremum seeking control with constraint conditions

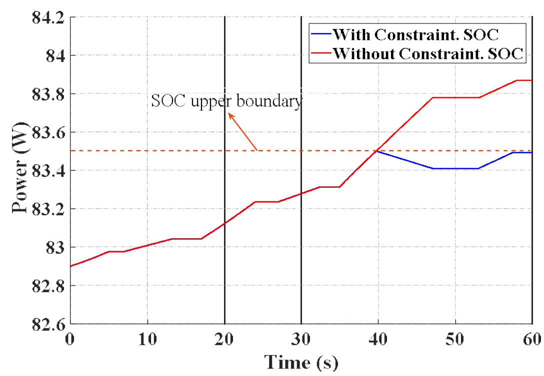


Fig. 4-18 SOC of battery with constraints.

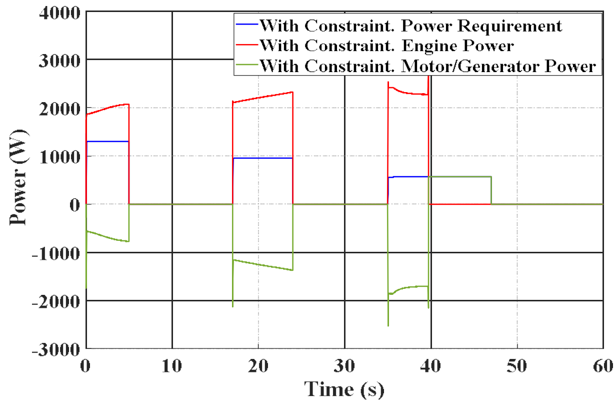


Fig. 4-19 Power distribution with constraints.

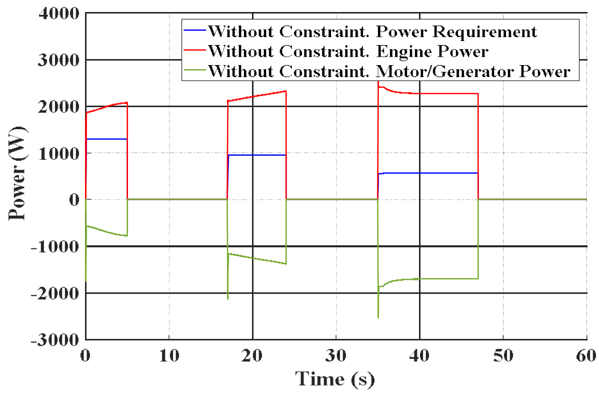


Fig. 4-20 Power distribution without constraints.

The goal of this simulation is to show why there should be a penalty function in the ESC. The limitation range of the battery SOC is set at 0.3 and 0.835. Hence, the initial SOC of the battery is assumed to be at 0.829 which is close to the upper boundary. Fig. 4-18 shows that when the SOC of the battery is in the limitation range from 0 to 40.5s, the output signal of the penalty function is zero. Then, the ICE continues to operate at its high-efficiency power while the excess power is charged into the battery through the electric motor/generator. When the SOC of the battery exceeds the upper limitation of 0.835 from 40.5 to 60s, the penalty function gives the output signal to stop charging into the battery and reduce the power of the ICE. Thus, at this time, only the ICE supplies power to the hydraulic system and the electric motor/generator stops working as shown in Fig. 4.19. Besides, the SOC is kept within the allowable range to ensure the safety of the system and the lifetime of the equipment. Without the constraint, the ICE continues to be maintained at high efficiency, and excess energy is stored in the battery via the generator mode of the electric motor/generator (Fig. 4-20). Then, SOC is out of the allowed range. From these simulation results, it can be seen that the proposed energy management strategy-based ESC is an online optimization method that can be applied to the EHCVP in real-time with unknown working cycles. This can overcome the weakness of energy management strategies based on offline optimization methods such as dynamic programming (DP) or Pontryagin's maximum principle (PMP).

4.6. Experimental results discussions

The proposed system with EHCVP Ⅱ can improve energy-saving efficiency. The speed and torque of the motor/ generator can be measured by the speed sensor and torque sensor. Hence, the working points of the motor/generator can be got, and the efficiency can be checked by an efficiency map. Then the energy consumption of the motor/generator can be calculated. Finally, the charge energy and discharge energy of the battery are got in the experiment. The test bench is controlled through the Simulink Desktop Real-Time mode, in which the control pogrom is built. The signals of each sensor are measured by Ni PCI card, which is installed in the industrial computer.

The effectiveness of the proposed system and the advantage of the energy management strategy-based ESC are not only proven by simulation but also verified on a real test bench. Due to the designed energy management strategy above, the gear ratios of the proposed EHCVP are adjusted during the operation the gear ratio 2 is used for the moving up process to improve the efficiency of the engine, and gear ratio 1 is operated for cylinder moving down. In contrast, the double clutch 1 is not integrated into the conventional EHCVP, the gear ratio, therefore, cannot be changed. By using the proposed EMS, the power requirement is distributed to the ICE and the electric motor/generator as shown in Fig. 4-21. During the lifting process of the boom cylinder, the powers of the ICE at the high-efficiency points are higher than the power requirements. Hence, the excess power from the ICE is charged to the battery by using the generator mode of the electric motor/generator.

Similar to the proposed system, the powers of the ICE and the electric motor/generator of the conventional EHCVP system are also distributed by the ESC as shown in Fig. 4-22. The electric motor/generator is used to compensate for the power of the ICE with the first 2 cycles using generator mode and the last cycle using motor mode.

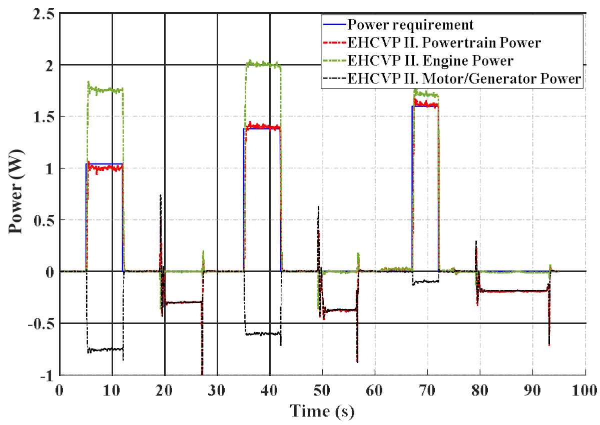


Fig. 4-21 Experimental results with EHCVP Ⅱ.

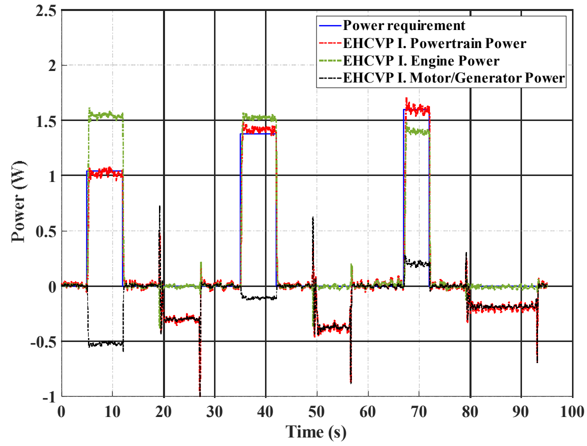


Fig. 4-22 Experimental results with EHCVP I.

A conventional system without EHCVP and EHCVP Ⅱ were also tested. The experimental results are shown in Fig. 4-23. In boom-up mode only ICE the hydraulic pump. The working points of the engine are different from those of EHCVP and EHCVP Ⅱ, because there is no electric motor/generator to provide additional energy. In boom-down mode, the cylinder moved down without energy regeneration.

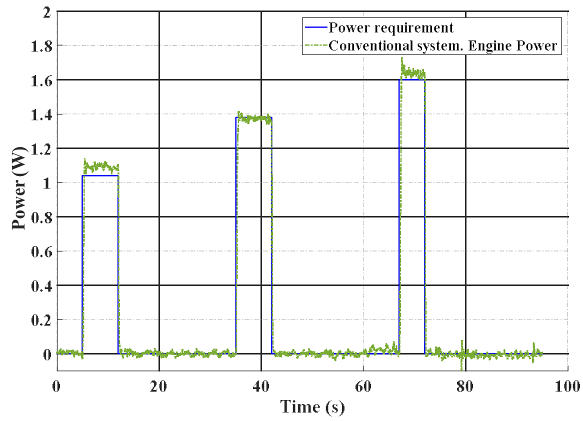


Fig. 4-23 Experimental results with conventional system.

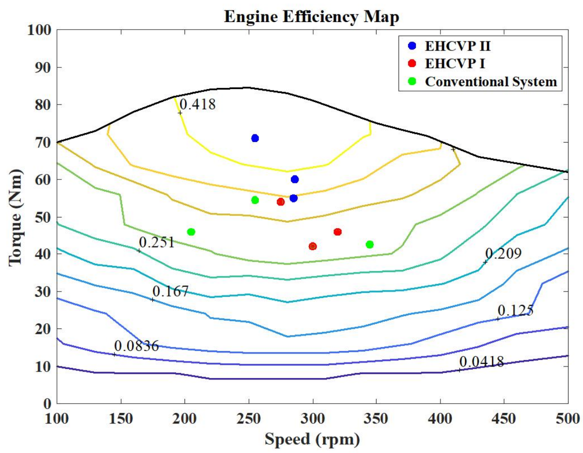


Fig. 4-24 Working points of engine.

The engine working points of EHCVP Ⅱ, EHCVP, and the conventional system are shown in Fig. 4-24 with blue color, red color, and green color, respectively. The engine working points of the conventional system are located in large speed areas because the large velocity of the cylinder is required. But the efficiency of the engine is low. The engine efficiency of EHCVP is higher than that of a conventional system due to the integration of the electric motor/generator. But the engine cannot work in the highest efficiency range. Even if the displacement of the hydraulic pump got the maximum value of 30 mL/rev, the engine torque cannot be increased to improve the engine efficiency further. The engine working points of EHCVP Ⅱ are located in the highest efficiency range, because the gearbox is used in the system, and a higher gear ratio of 1:1.3 is selected to increase the engine torque.

Engine efficiency is the key point to decide the energy consumption of the system. But the other components also affect energy consumption. Hence, the experimental energy consumption of the total system is summarized in table 4-3 to verify the energy-saving efficiency of the proposed EHCVP Ⅱ in the hydraulic excavator boom system.

Table 4-2 Comparison of energy consumption

System	Eeng(kJ)	ΔEbat(kJ)	Etot(kJ)	ŋsav
EHCVP Ⅱ	73.22	8.45	64.77	0.45
EHCVP	72.31	3.48	68.83	0.37
Conventional System	75.8	0.00	75.8	0

4.7. Chapter summary

To reduce the energy consumption and emission of hydraulic excavators, a novel hybrid hydraulic excavator is proposed in this chapter with the innovative EHCVP Ⅱ and the energy regeneration system. An ESC with constraint penalty is proposed as the energy management strategy, in which the speed and torque of the engine are controlled in its high-efficiency range. Based on the experimental results, the energy consumption can be reduced in boom-up mode, and the potential energy of the boom can be regenerated in boom-down mode. Compared with the conventional system and the current EHCVP, the EHCVP Ⅱ and the improved ECMS can improve the working efficiency of the engine further. The experimental results show that the proposed system can save 14.55% of the energy. In our research, one liter of diesel fuel has an energy content of appropriately 38 MJ which is appropriate for 10 kWh. Besides, diesel produces 2.63 kg of CO_2 per liter of the diesel vehicle. Therefore, the fuel consumption of the EHCVP II, EHCVP I, and conventional system are 0.0017 L, 0.0018 L, and 0.0019 L, respectively. Taking a 48-t excavator as an example, the 48-t excavator is 160 times larger than the testbench. Then, according to the 3 cycles of 150 s, working hours of 10 h per day, the total fuel saving is 7.68 L per day of a 48-t excavator. According to the calculation of 250 days per year [6], the annual fuel consumption can be reduced by 1920 L. Based on the carbon dioxide production of diesel, the carbon dioxide emission can be reduced by 5049 kg per year. Hence, the proposed system can reduce fuel consumption and carbon dioxide emission effectively.

Chapter 5
ADVANCED ENERGY MANAGEMENT STRATEGY

5.1. Introduction

5.1.1. Overview

On the other hand, concerning the complexity of the HE, it might be impossible to capture its dynamics just by mathematical modeling, which is required by various energy management schemes. Hence, a model-free, real-time energy management strategy would be a more suitable candidate for the HE. Teodorescu et al. applied the ECMS for a parallel hybrid forklift to minimize fuel consumption and maintain the state of charge (SOC) of the supercapacitor in the optimal range by changing the engine speed corresponding to the load condition [33]. Anders et al. used the ECMS for a parallel powertrain HE with considering the power consumption of the ICE, and the inner and kinetic power of the electric motor in a Hamiltonian function [34]. By minimizing this function, the optimal fuel control of the ICE could be estimated, and the dynamics of the powertrain became smoother. Yu et al. developed a real-time EMS based on a DP - extremum seeking (ES) [35]. In which, DP was used to ensure the approximate global energy optimality and SOC sustainability, while ES compensated the control signal from the DP to reduce fuel consumption in real-time operation. However, these studies have just focused on maximizing the ICE efficiency and reducing energy consumption without considering battery aging.

5.1.2. Proposed energy management strategy based on fuzzy ESC

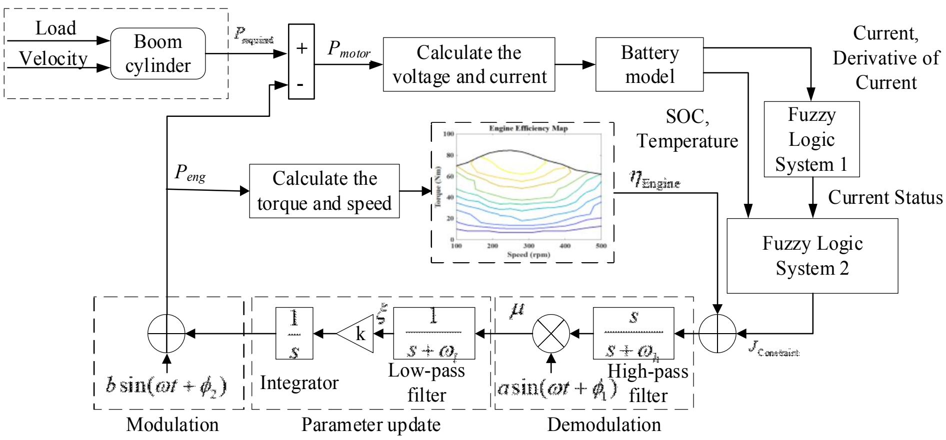


Fig. 5-1 Proposed fuzzy extremum seeking based energy management strategy.

Thus, in addition to the proposition of the innovative EHCVP solution, an online energy management strategy based on the extremum seeking control (ESC) is also developed in this chapter to switch the gear ratio and efficiently distribute the power to the EHCVP (Fig. 5-1). Here, the conventional penalty function is caused by suddenly changing the powerful engine and making the unstable powertrain when the considered parameter such as SOC of battery beyond the allowable range is replaced by a fuzzy logic system. In detail, the fuzzy logic system is constructed based on considering the battery aging with its input parameters are the current, SOC, and temperature of the battery. During the operation, the fuzzy logic system estimates the output penalty value adjusting the power reference of each power source depending on the battery status.

5.2. Lithium-Ion battery degradation model

The capacity loss can be estimated as follow:

$$Q_{loss}(\sigma, Ah) = \sigma(I_c, \theta, SOC)\,\mathrm{Ah}^{z} \tag{5.1}$$

where Ah is the accumulated charge throughput, z is the power law exponent that represents Ah throughput dependence, $z = 0.52$, I_c is the charging current, $\theta$is the test temperature, and σ is a nonlinear function of severity factors, which can be expressed as:

$$\sigma = \left(A_{bat} SOC + B_{bat}\right)\exp\left(\frac{-E_{a} + \eta I_c}{R_g\left(273.15 + \theta\right)}\right) \tag{5.2}$$

where A_{bat}, B_{bat}, and η are determined by using the curve fitting method, $\eta = -63.54$, $A_{bat} = -74.99$, $B_{bat} = 12895.92$, R_g is the universal gas constant, which equals to 8.314 J/mol/K, E_a is the activation energy, which equals to 31700 J/mol [87]. The accumulated charge throughput Ah which can be seen as the battery capability loss is estimated:

$$Ah = \int_0^t \sigma \left|I_c(t)\right| dt \tag{5.3}$$

Then, the State of Health (SoH) can be calculated as follow:

$$SOH(t) = \frac{Q_{bat,nom} - Q_{loss}(t)}{Q_{bat,nom}} \tag{5.4}$$

5.3. Constraint problems in the ESC

5.3.1. Fix-Constraint ESC

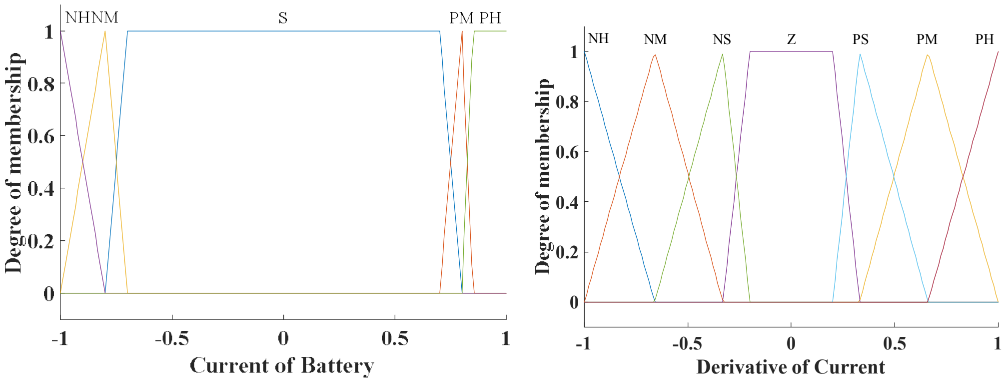
In this ESC method, $J_{\text{Constraint}}$ can be interpreted as a virtual disturbance that opposes the engine efficiency in value and guarantees the safety of the battery by considering the SOC, temperature, and current as input parameters [88].

$$J_{\text{Constraint}} = -\sum_{x=\{SOC, Ic, T\}} k_{\mathrm{x}} max\left\{k_{1\mathrm{x}}\frac{x_{\min} - x}{x_{\min}}, 0, k_{2\mathrm{x}}\frac{x - x_{max}}{x_{max}}\right\}^2 \tag{5.5}$$

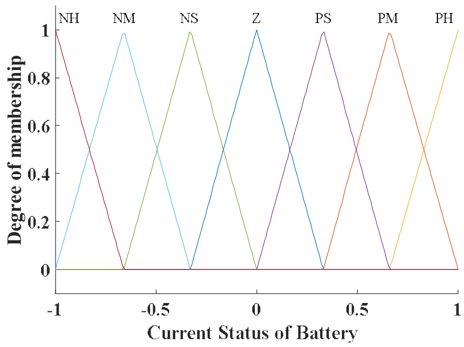
$$\text{with } \begin{cases} \left[k_{1SOC}, k_{2SOC}\right] = [1,1] \\ \left[k_{1Ic}, k_{2Ic}\right] = [-1,1] \\ \left[k_{1T}, k_{2T}\right] = [0,1] \end{cases}$$

where k_{x} denote penalty gain, which is turned and fixed during the operation, $x_{min,}$ and x_{max} represent the design boundaries.

5.3.2. *Proposed Fuzzy-Constraint ESC*



a) Input parameters of fuzzy loop 1

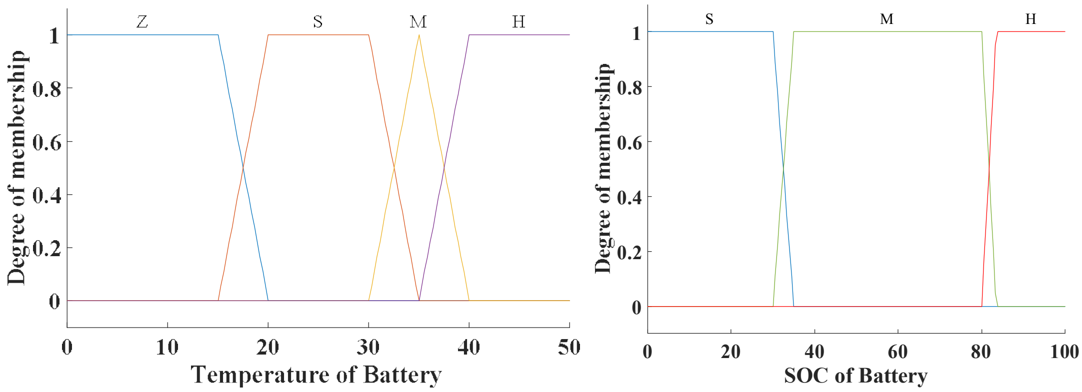


b) Output parameter of fuzzy loop 1

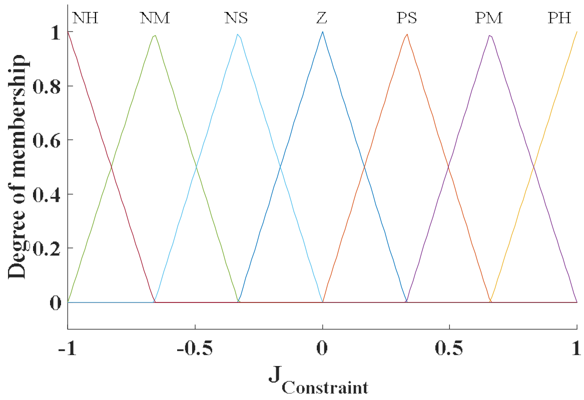
Fig. 5-2 MFs for input and output of battery's current status.

Table 5-1 Fuzzy rule of current status

Current Status		**Current of Battery**				
		NH	**NM**	**S**	**PM**	**PH**
Derivative of Current	**NB**	NH	NS	NS	PH	PH
	NM	NH	NS	NS	PH	PH
	NS	NH	NS	Z	PM	PH
	Z	NH	NS	Z	PS	PH
	PS	NH	NS	Z	PS	PH
	PM	NH	NM	PS	PS	PH
	PB	NH	NH	PS	PS	PH



a) Input parameters of fuzzy loop 2



b) Output parameter of fuzzy loop 2

Fig. 5-3 MFs for input and output of penalty function $J_{constraint}$.

The selection of the design parameter k_x demonstrates a trade-off between engine efficiency and battery usage. A large value k_x would prevent the battery unit from overcharging or over-discharging, whereas a small value would result in higher engine efficiency. However, with a fixed value k_x , the ICE can be suddenly turned on or off when the considered parameters in the penalty function reach their rated values. Besides, even if the SOC battery exceeds the minimum boundary, the battery must discharge the power to the system due to the property of the penalty equation (see (14)). This could result in the SOC not being maintained within its desired operating region.

To overcome this drawback, the conventional penalty function in ESC is replaced by a fuzzy logic system (FLS) which is designed with two fuzzy loops based on the consideration of battery aging. The fuzzy loop 1 is used to capture the current dynamic of the battery. Here, the fuzzy inputs are normalized values of the battery current and its derivative (Fig. 5-2a). The maximum current is decided by the battery management system. Both the input ranges are therefore within [-1,1] (negative and positive currents are discharging and charging, respectively). The fuzzy output of loop 1 (Fig. 5-2b), together with SOC and temperature of the battery are fed into fuzzy loop 2 as inputs (see Fig. 5-3). The output of the fuzzy loop 2 is $J_{\text{Constraint}}$ which is used in Eq. (5.5). The fuzzy subsets of the current, derivative of current, temperature, and SOC are divided into five, seven, four, and three triangle membership functions (MFs) whereas "Z", "S", "NS", "PS", "M", "NM", "PM", "H", "NH", "PM" are "Zero", "Small", "Negative Small", "Positive Small", "Medium", "Negative Medium", "Positive Medium", "High", "Negative High", "Positive High", respectively. Depending on the characteristic of each parameter, the shape sizes are set to define the safe and risky working regions which can be used to decide the fuzzy rule. Meanwhile, the output value of the tuning FLS is divided into seven MFs with the same intervals and the same shape sizes. Then, the fuzzy rules are designed so that the output value corresponding to $J_{\text{Constraint}}$ value can be adjusted as listed in Tables 5-1 to 5-4. As an example, when having low SOC and temperature, $J_{\text{Constraint}}$ the FLC can adjust the power of ICE to not only charge the battery but also supply it to the system. Besides, the FLC can maintain the current within defined boundaries.

Table 5-2 Fuzzy rule of current status and temperature with $J_{constraint}$

$J_{Constraint}$		Current Status						
		NH	**NM**	**NS**	**Z**	**PS**	**PM**	**PH**
Temperature	**Z**	NH	NH	NH	NH	NH	PH	PH
	S	NH	NS	NS	Z	PS	PS	PH
	M	NH	NM	NM	NS	PM	PM	PH
	H	NH	NH	NH	NH	NH	PH	PH

Table 5-3 Fuzzy rule of current status and SOC with $J_{constraint}$

$J_{Constraint}$		Current Status						
		NH	**NM**	**NS**	**Z**	**PS**	**PM**	**PH**
SOC	**S**	NH	NM	NM	NM	NM	NS	PH
	M	NH	NS	NS	Z	PS	PS	PH
	H	NH	PS	PM	PM	PM	PH	PH

Table 5-4 Fuzzy rule of SOC and temperature with $J_{constraint}$

$J_{Constraint}$		Temperature			
		Z	**S**	**M**	**H**
SOC	**S**	NH	NM	NM	NH
	M	NH	Z	Z	NH
	H	NH	PM	PM	NH

5.4. Simulation results and discussions

5.4.1. Simulation description

Table 5-5 Initial values of SOC and temperature in different cases

Initial value	Case 1: High current	Case 2: High SOC	Case 3: High SOC and high temperature	Case 4: Low SOC, low temperature, and high current
SOC	60	83	83	15
Temperature	25	25	39.5	15

An EHCVP simulation model is constructed by using a co-simulation between AMESim software version 2020.1 and Matlab/Simulink 2017a. First, a comparison between the proposed EHCVP and the conventional EHCVP [86] using the ESC and working cycles is carried out to confirm the benefits of using this new EHCVP. Second, four scenarios with different initial parameters of the battery are carried out on the proposed EHCVP to prove the effectiveness of the proposed fuzzy ESC compared with three EMSs as depicted in Table 5-5. The three comparative EMSs are non-constraint ESC, fixed constraint ESC, and ECMS. Based on the characteristics of the EHCVP, the cost function is defined as.

$$\dot{m}_{total} = E_{eng} + \omega E_{motor} \tag{5.6}$$

where, $\dot{m}_{total}$ is the total equivalent fuel consumption, E_{eng} and E_{motor} are the equivalent energy consumptions of the engine and electric motor, respectively. The reward and punishment coefficient ω can be obtained by:

$$\omega = 1 - \frac{2\mu\left(SOC(t) - 0.5\left(SOC_{\min} + SOC_{max}\right)\right)}{SOC_{max} - SOC_{\min}} \qquad (5.7)$$

where, the μ represents a balance coefficient, and its value in this study is 0.6.

Case 1: High current

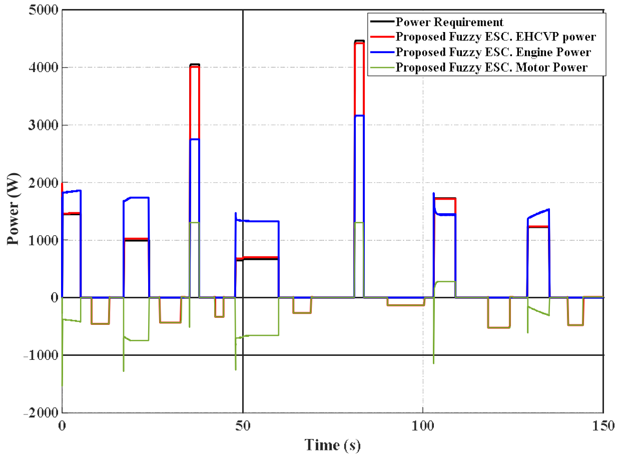


Fig. 5-4 Power distribution by using proposed Fuzzy ESC in case 1.

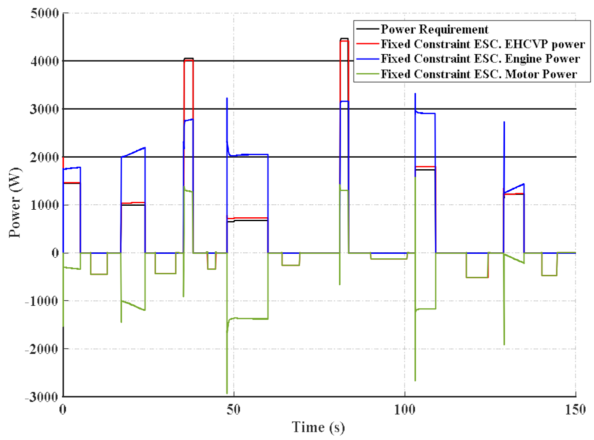


Fig. 5-5 Power distribution by using Fixed Constraint ESC in case 1.

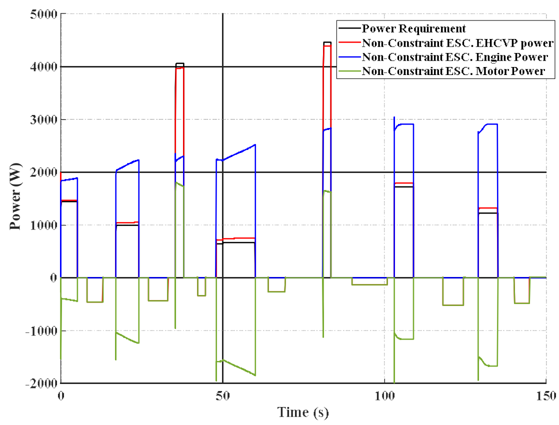


Fig. 5-6 Power distribution by using Non-Constraint ESC in case 1.

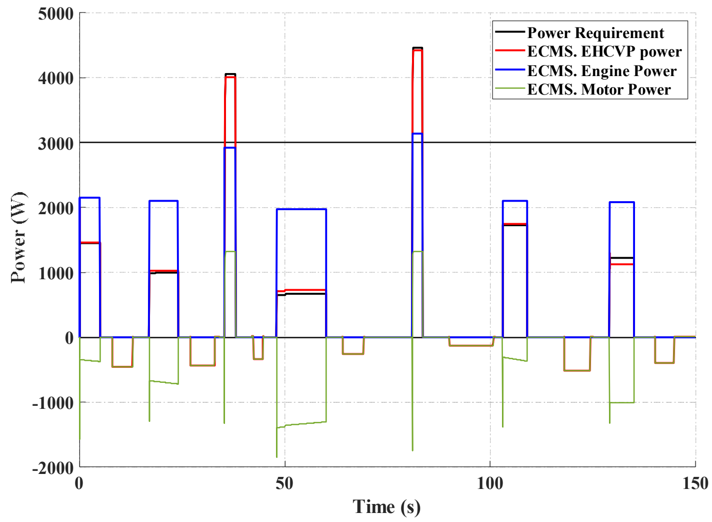


Fig. 5-7 Power distribution by using ECMS in case 1.

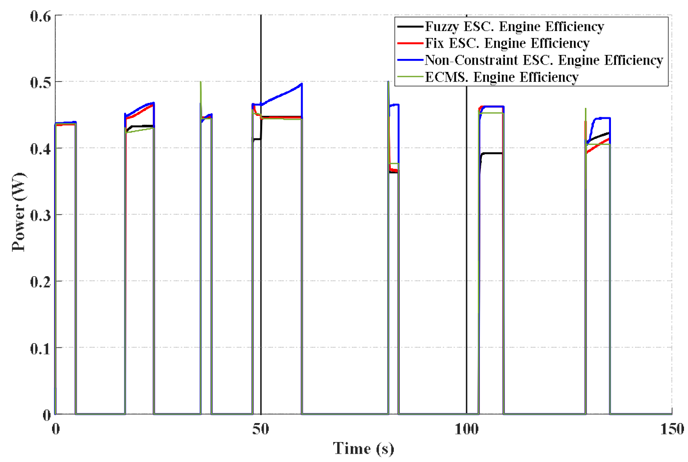


Fig. 5-8 Engine efficiencies with different control strategies in case 1.

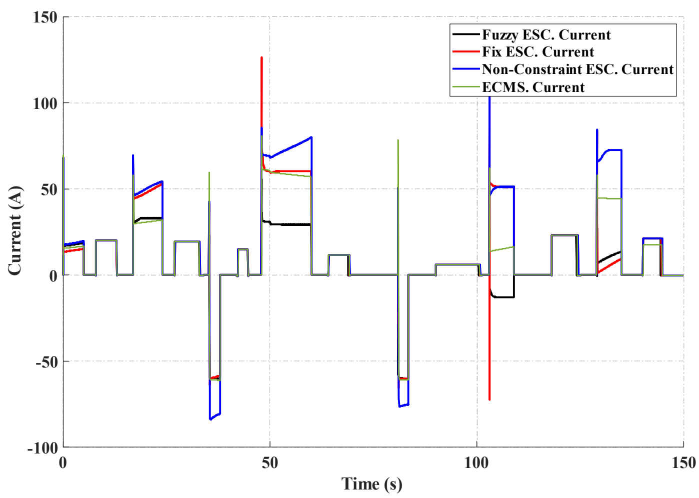


Fig. 5-9 Current of battery with different control strategies in case 1.

To fully investigate the system performance and evaluate the effectiveness of the proposed energy management strategy-based Fuzzy ESC, an EHCVP simulation model is constructed by using a co-simulation between the AMESim software version 2020.1 and Matlab/Simulink 2017a. Due to the designed energy management strategy above, the gear ratios of the proposed EHCVP are adjusted during the operation where the ratio 1.3 is used for the moving-up process to improve the efficiency of the engine, and ratio 1 is operated for the cylinder moving down.

The first simulation is performed in the case of the high current operation of the battery as shown in Figs 5-4 to 5-7. The working boundary of the current is decided in the range from -60A to 60A. Besides, the initial SOC and temperature of the battery were set at 60% and 25°C, respectively. The simulation results indicated that the ESC without constraint could achieve the highest engine efficiency (Fig. 5-8). However, this EMS could not maintain the current in the desired range leading to an increase in battery losses and reduced SOH (Fig. 5-9). With other EMS, the current of the battery was limited in the boundary and thus, the battery durability was enhanced. In which, the proposed fuzzy ESC had the lowest capacity loss and highest SOH after 50000 working cycles (Table 5-6). Compared with the ESC without constraint, the capacity loss of the battery by using the proposed fuzzy ESC could reduce appropriately by 33% and the SOH of the battery could increase by 3.35%. Besides, the power tracking of the proposed EMS was also good performance.

Case 2: High SOC

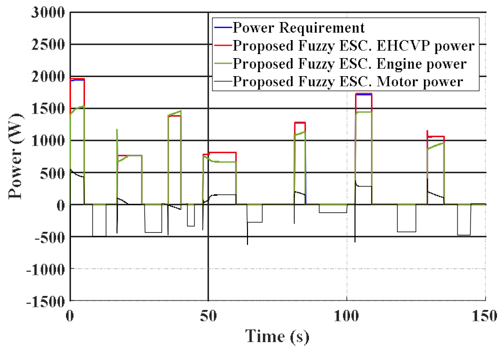


Fig. 5-10 Power distribution by using proposed Fuzzy ESC in case 2.

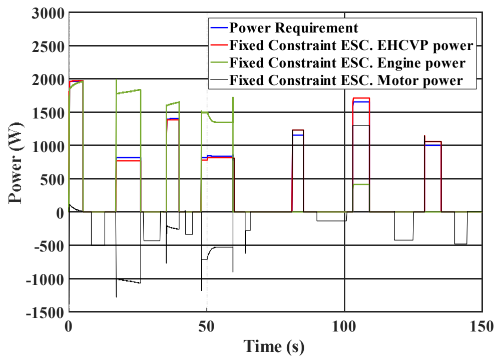


Fig. 5-11 Power distribution by using Fixed Constraint ESC in case 2.

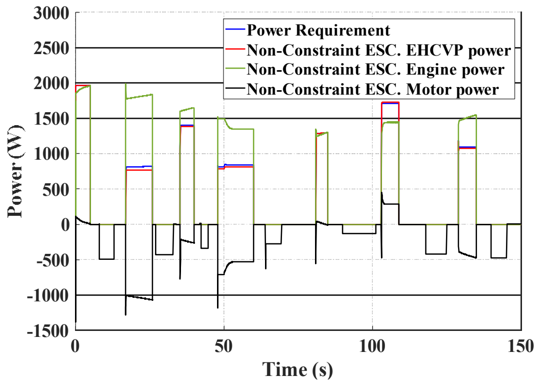


Fig. 5-12 Power distribution by using Non-Constraint ESC in case 2.

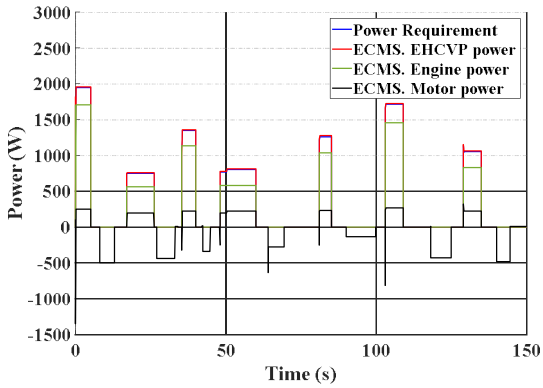


Fig. 5-13 Power distribution by using ECMS in case 2.

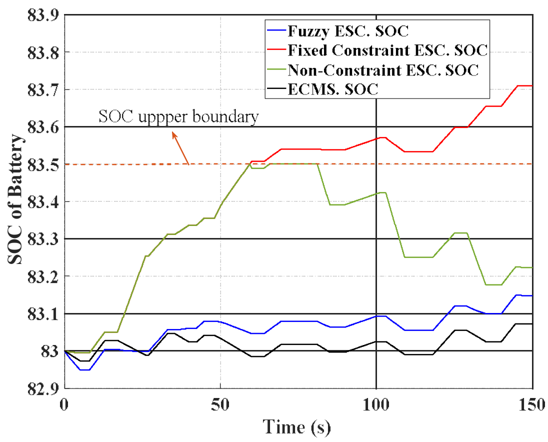


Fig. 5-14 SOC of battery with different control strategies in case 2.

The second simulation is conducted under high SOC of battery condition which was set at 83% (Figs. 5-10 to 5-13). Without considering the battery status, the non-constraint ESC continues to maintain the engine working in the high-efficiency region. This results in the battery SOC exceeding the desired upper boundary (83.5%) and reducing the battery life (Fig. 5-14). This problem could be overcome by using the fixed constraint ESC with maintaining the SOC in the limitation. During the operation, when the SOC of the battery reached the upper limitation value, the engine was suddenly turned off and the power requirement was supplied by the electric motor to reduce the SOC value. However, to supply power to the system without support from the engine, the battery had to work with a high current and rapidly increased the temperature. Therefore, compared with non-constraint ESC, the capacity loss was increased by 22.1% and the SOH was quickly reduced by 1.35%. The trade-off was that the engine's efficiency was reduced compared to other EMSs. With the ECMS and proposed fuzzy ESC, when the SOC was close to the maximum value, the engine reduced the charging power to the battery via an electric motor to maintain the SOC in the working range and increase the SOH of the battery (Table 5-6). In which, the proposed fuzzy ESC had the lowest capacity loss and highest SOH. Besides, the engine efficiency was higher than the ECMS.

Case 3: High SOC and high temperature

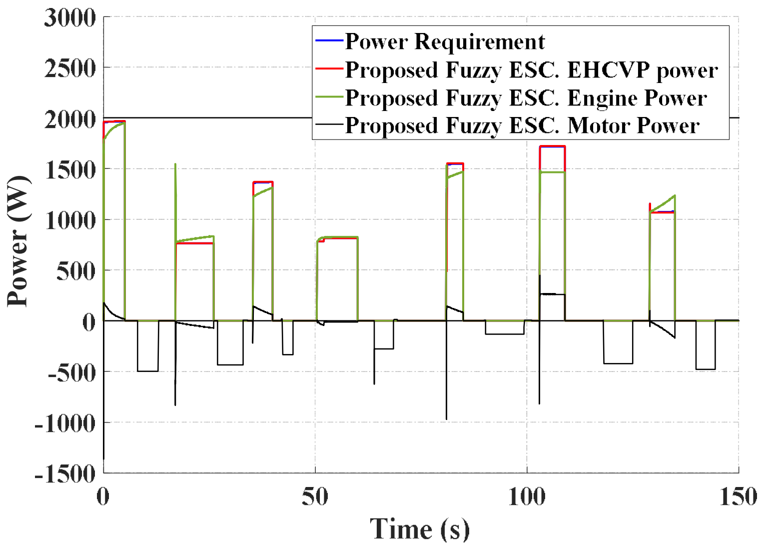


Fig. 5-15 Power distribution by using proposed Fuzzy ESC in case 3.

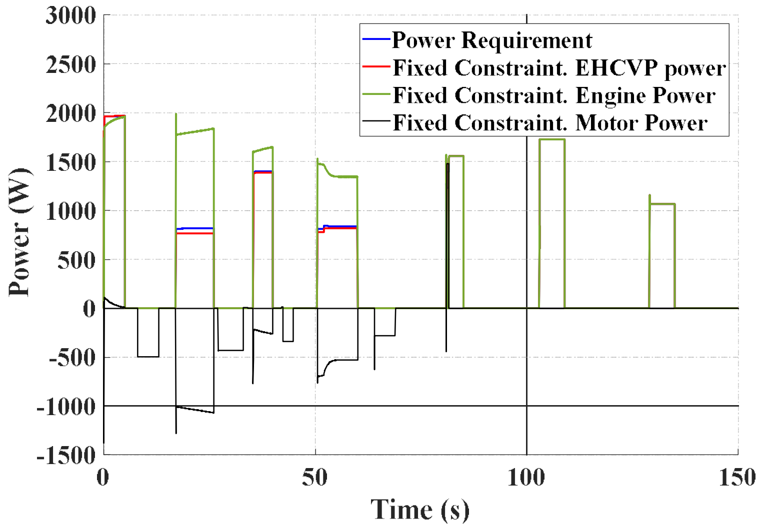


Fig. 5-16 Power distribution by using Fixed Constraint ESC in case 3.

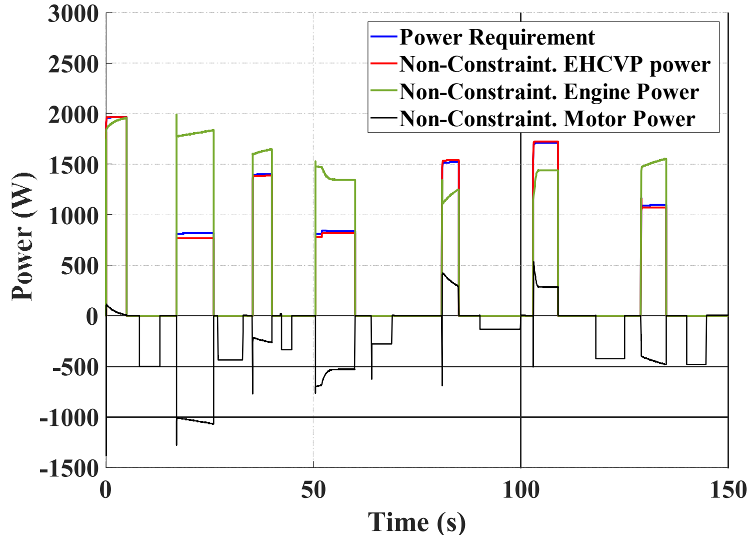


Fig. 5-17 Power distribution by using Non-Constraint ESC in case 3.

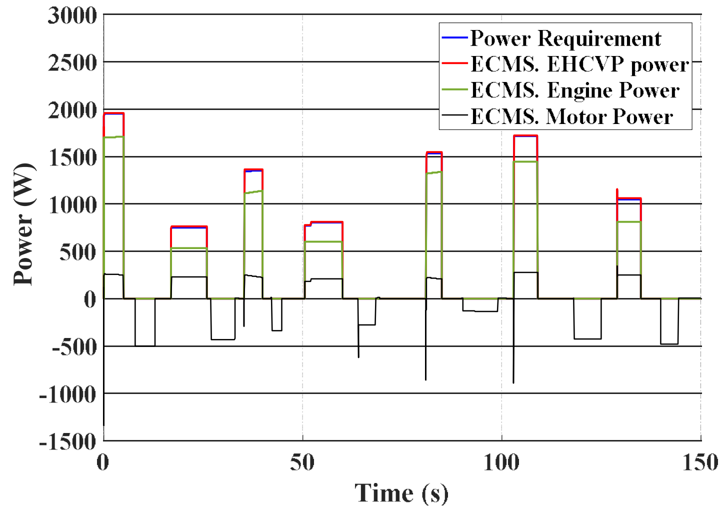


Fig. 5-18 Power distribution by using ECMS in case 3.

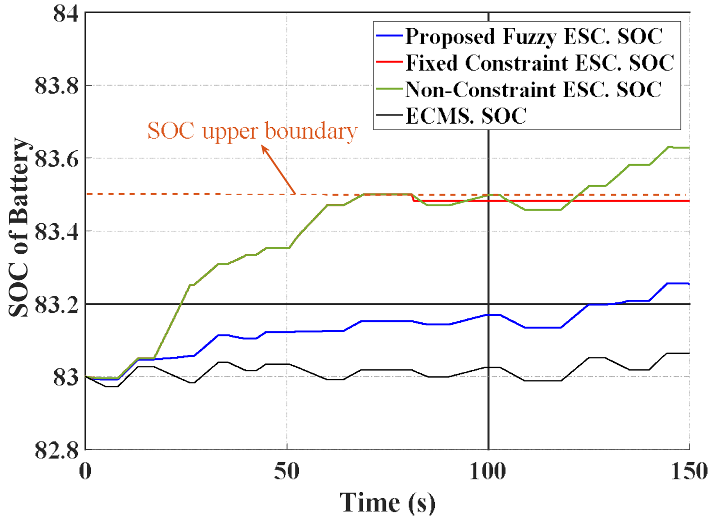


Fig. 5-19 SOC of battery with different control strategies in case 3.

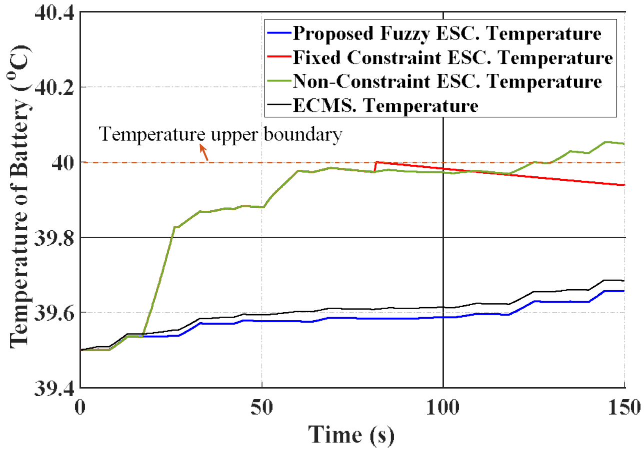


Fig. 5-20 Temperature of battery with different control strategies in case 3.

The third simulation is used to verify the performance of the proposed EMS under high SOC and high temperature of battery which were set at 83% and 39.5°C, respectively (Figs. 5-15 to 5-18). In this case, the non-constraint ESC maintained the engine work in the high-efficiency region without considering the constraints. The SOC and temperature of the battery went beyond the upper boundary; therefore, the SOH was quickly reduced (Fig. 5-19, 5-20). With the fixed constraint ESC, the SOC and temperature were the considered factors in the penalty function. Thus, when these parameters reached the maximum values, the motor stopped working to protect the battery and the power requirement was supplied by the engine. Then, the capacity loss was reduced by 18.5% and the SOH could increase by 2%. Different from the two EMSs above, the proposed fuzzy ESC and EMCS reduce the charging power to the battery during the operation of this condition. Therefore, the SOC and temperature of the battery did not reach the maximum values. Then, the battery durability could be enhanced where the proposed fuzzy ESC achieved the best performance with the capacity loss reduced by 31% and the SOH could be improved by 3.4% (Table 5-6).

Case 4: Low temperature and low SOC

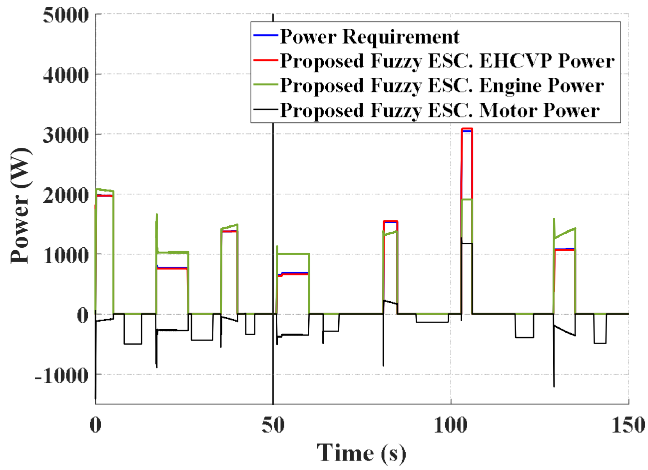


Fig. 5-21 Power distribution by using proposed Fuzzy ESC in case 4.

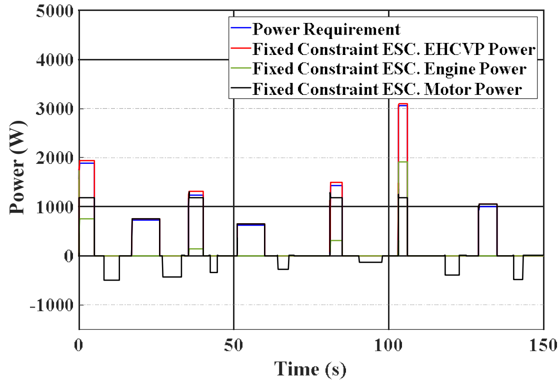


Fig. 5-22 Power distribution by using Fixed Constraint ESC in case 4.

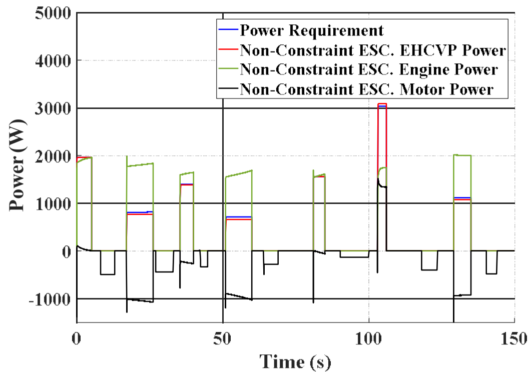


Fig. 5-23 Power distribution by using Non-Constraint ESC in case 4.

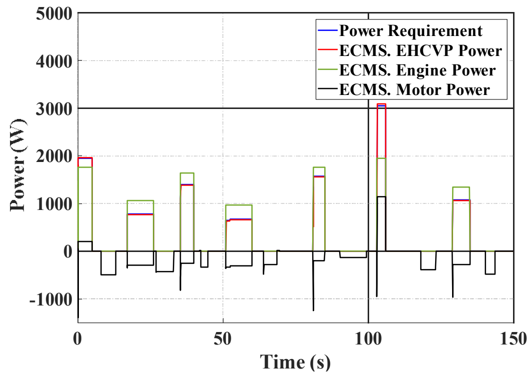


Fig. 5-24 Power distribution by using ECMS in case 4.

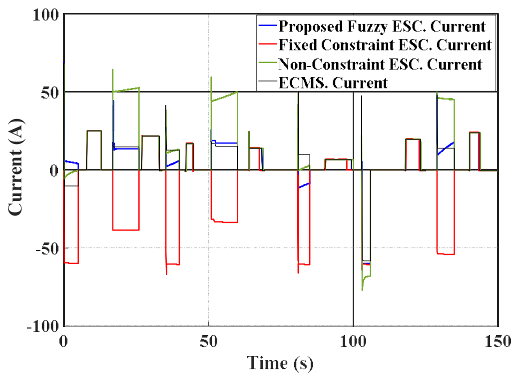


Fig. 5-25 Current of battery with different control strategies in case 4.

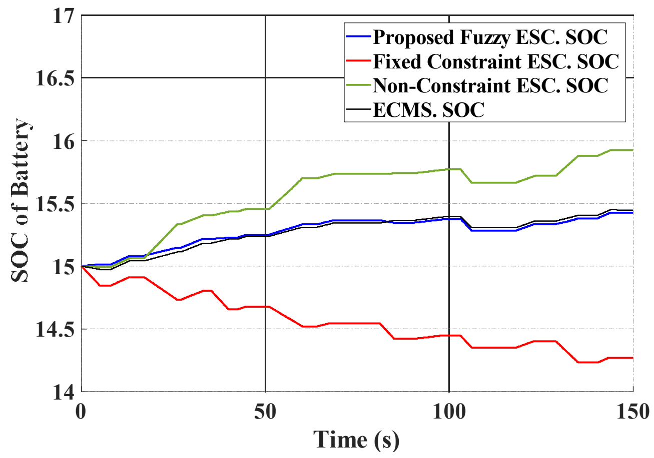


Fig. 5-26 SOC of battery with different control strategies in case 4.

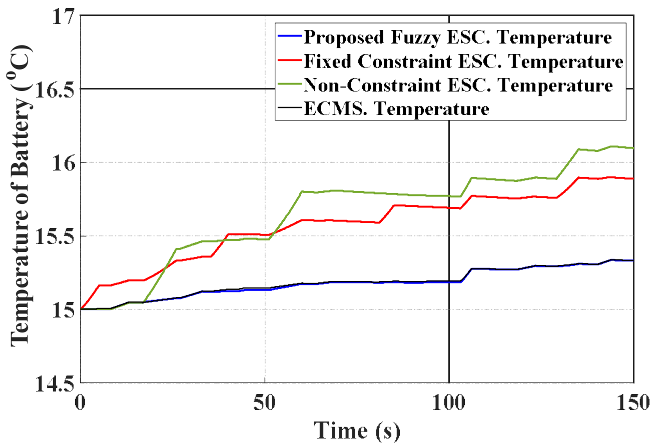


Fig. 5-27 Temperature of battery with different control strategies in case 4.

The final simulation focused on proving the effectiveness of the proposed fuzzy ESC under low SOC, low temperature, and high current conditions where the initial SOC and temperature were set at 15% and 15oC, respectively (Figs. 5-21 to 5-24). The characteristic of the penalty function is a square function, the engine was turned off and the required power was supplied by the motor and the battery when the considered factors in the penalty function went beyond the desired boundary. Even if the initial SOC and temperature of the battery were low values, the motor and battery had to discharge power to supply the system and the value of the SOC continuously decreased (Figs. 5.25 to 5.27). Therefore, the SOH of the battery by using the fixed constraint ESC was lowest in this working condition. Different from the fixed constraint ESC, other EMSs increased the power from the engine to not only supply the power to the system but also charge the battery, the SOC and temperature, therefore, were increased. However, without including the constraints in the penalty function, the non-constraint ESC could not guarantee the maximum current of the battery. Meanwhile, the proposed ESC and ECMS not only increased the SOC and temperature of the battery but also maintain the current in the desired working range. In which, the durability of the battery by using the proposed ESC has been enhanced by 1.73% SOH compared with the non-constraint ESC (Table 5-6).

Table 5-6 Comparation table of simulation results of a 50000 cycles projection

Working Condition	Criteria	Non-Constraint ESC	Fixed Constraint ESC	Proposed Fuzzy ESC	ECMS
High Current	Power following error	11.8%	9.8%	4.7%	4.5%
	Energy Consumption	8681 MJ	8495 MJ (-2.1%)	7611 MJ (-12.3%)	8940 MJ (+3%)
	Engine Efficiency	0.456	0.435	0.4264	0.452
	State of Health	89.85%	91.54 %	93.2%	91.57%
High SOC	Power following	6.2%	6.5%	5%	4.5%
	Energy Consumption	7768 MJ	6290 MJ (-19%)	6470 MJ (-16.7%)	6522 MJ (-16%)
	Engine Efficiency	0.412	0.346	0.4	0.37
	State of Health	93.87%	92.52%	95.37%	95.05 %
High SOC and high temperature	Power following	6.25%	6.7%	5.1%	4.5%
	Energy Consumption	7158 MJ	7477 MJ (+4.5%)	6662 MJ (-3.8%)	6515 MJ (-9%)
	Engine Efficiency	0.425	0.4	0.365	0.35
	State of Health	89.2 %	91.2%	92.6%	91.1%
Low temperature, low SOC, and high current	Power following	7.5%	5.6%	5.3%	5.2%
	Energy Consumption	7382 MJ	3945 MJ (-46.6%)	6750 MJ (-4.9%)	6935 MJ (-6%)
	Engine Efficiency	0.425	0.25	0.385	0.388
	State of Health	93.5 %	92.8 %	95.23 %	95.1 %

5.4.2. Experiment description

Case 1: High current

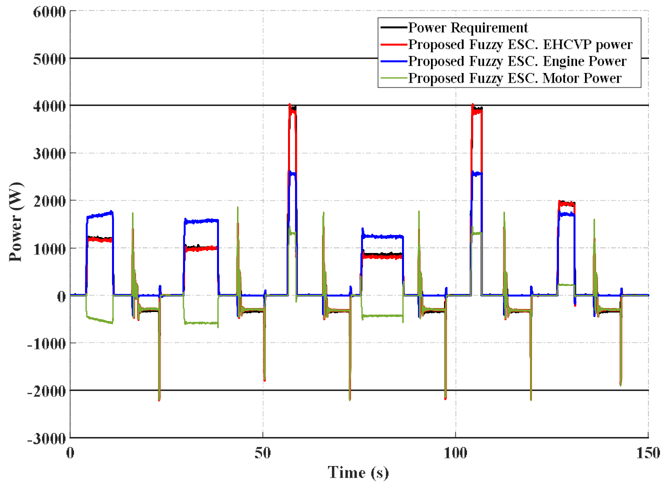


Fig. 5-28 Power allocation by using proposed Fuzzy ESC in case 1.

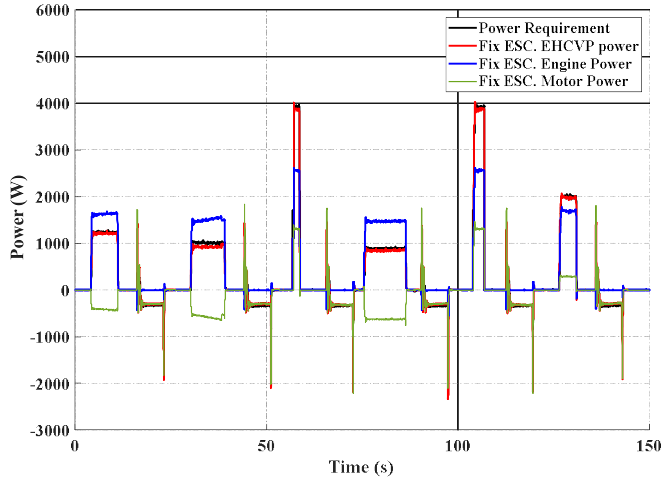


Fig. 5-29 Power allocation by using Fixed Constraint ESC in case 1.

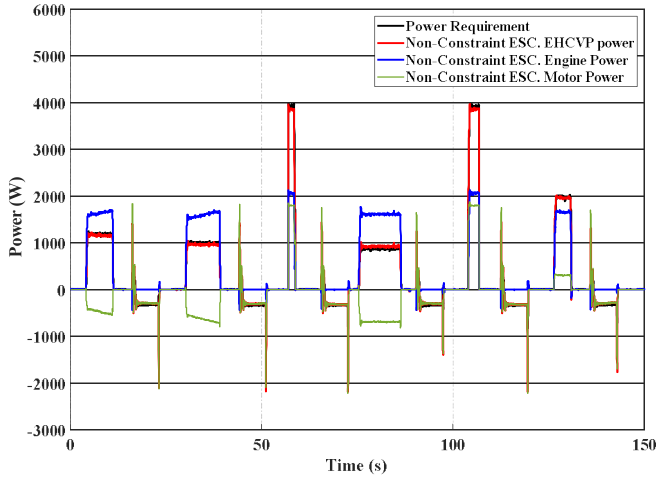


Fig. 5-30 Power allocation by using Non-Constraint ESC in case 1.

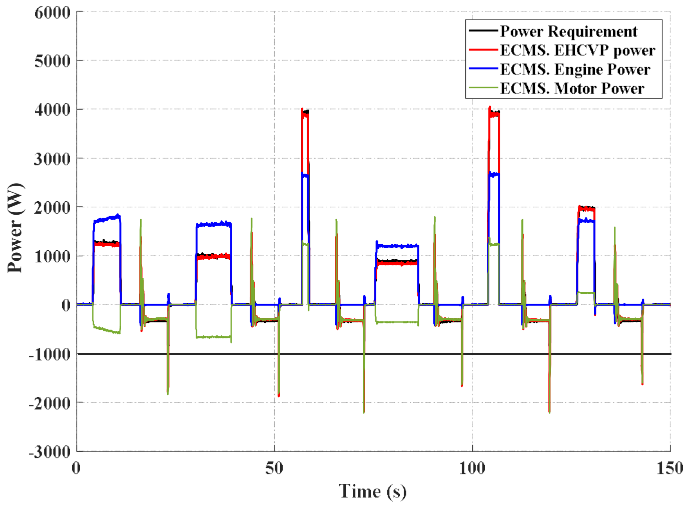


Fig. 5-31 Power allocation by using ECMS in case 1.

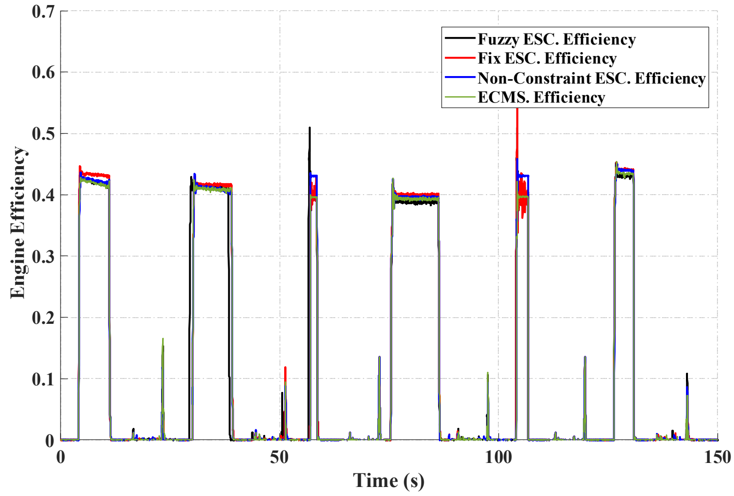


Fig. 5-32 Efficiency of engine in case 1 based on experiment results.

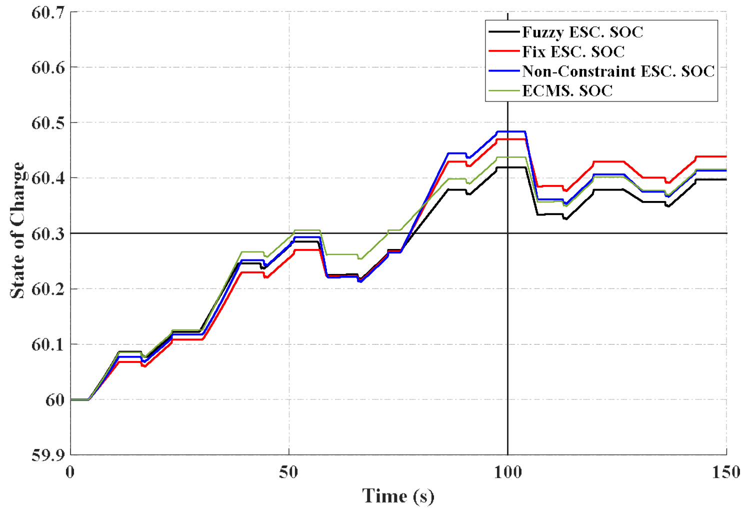


Fig. 5-33 SOC of battery in case 1 based on experiment results.

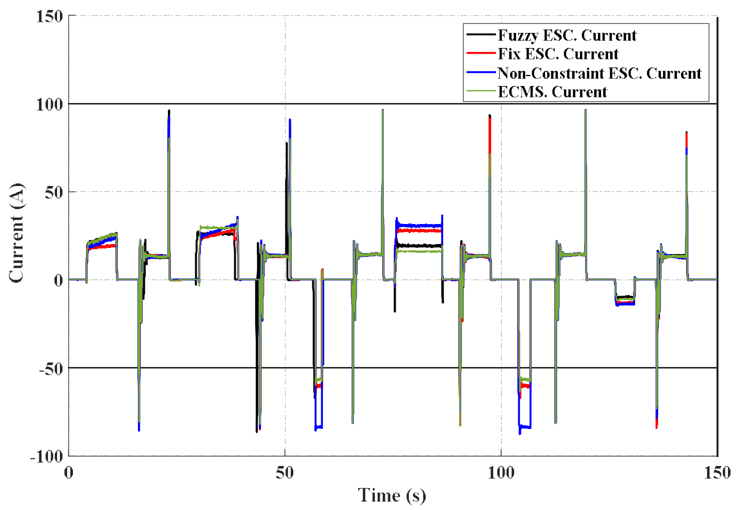


Fig. 5-34 Current of battery in case 1 based on experiment results.

Case 2: High SOC

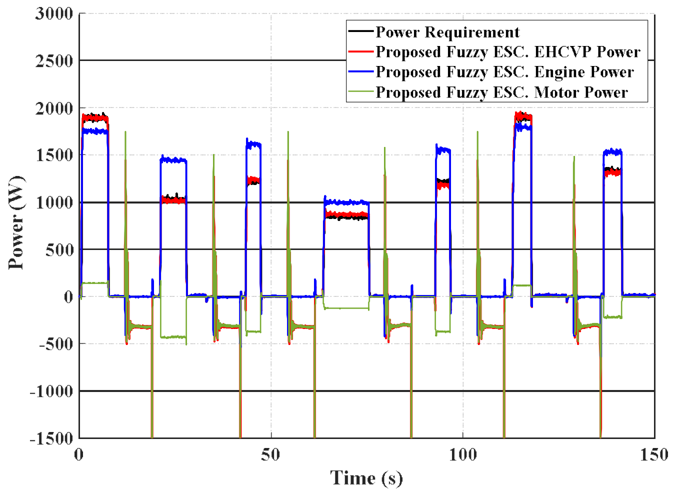


Fig. 5-35 Power allocation by using proposed Fuzzy ESC in case 2.

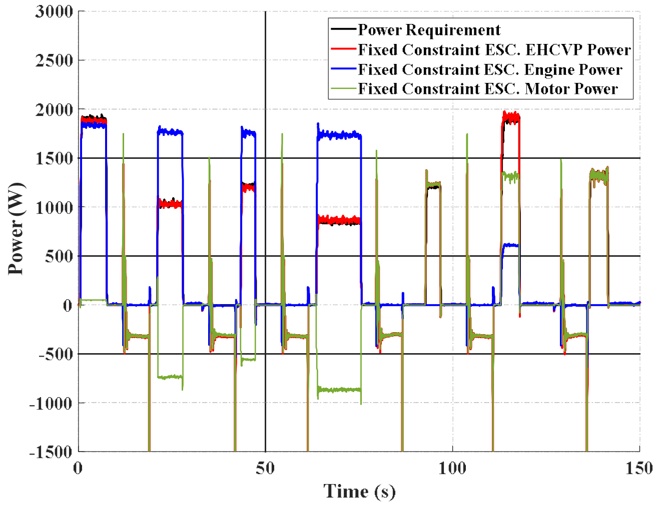


Fig. 5-36 Power allocation by using Fixed Constraint ESC in case 2.

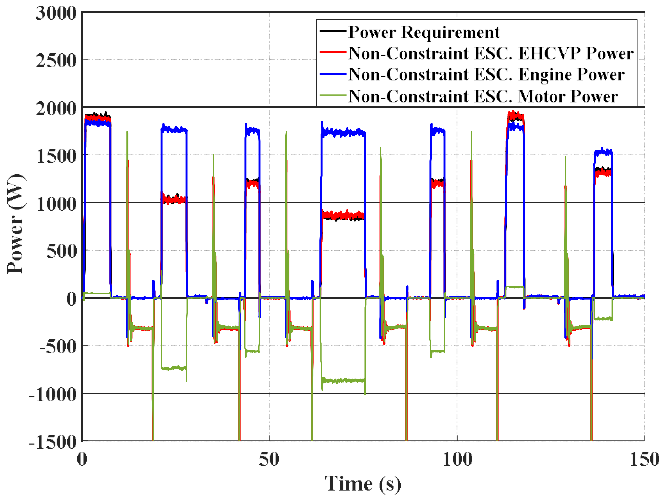


Fig. 5-37 Power allocation by using Non-Constraint ESC in case 2.

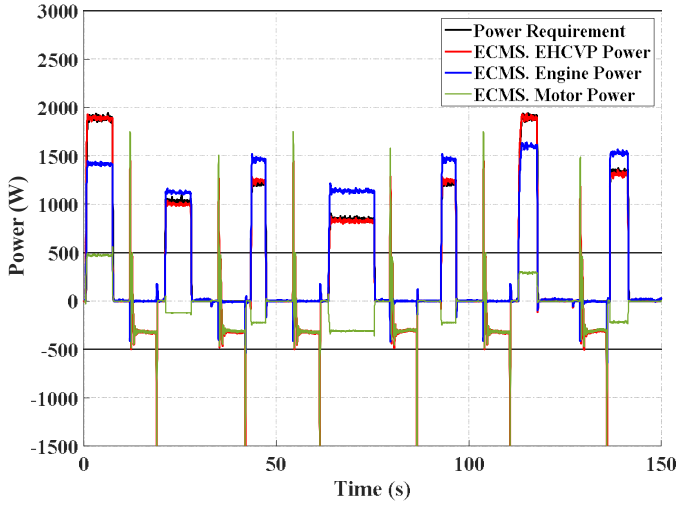


Fig. 5-38 Power allocation by using ECMS in case 2.

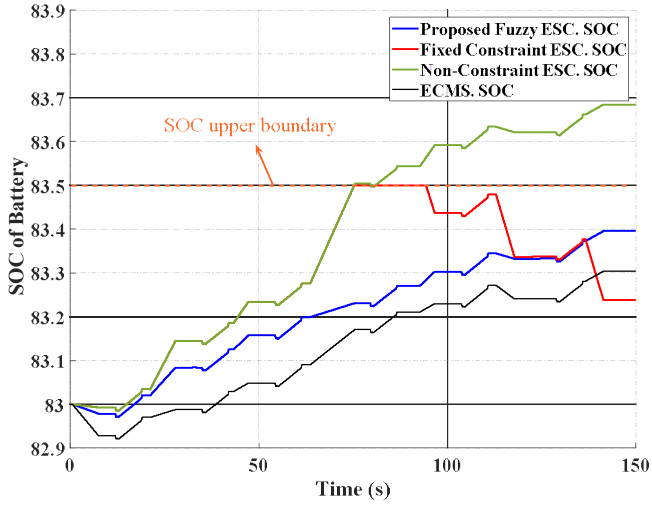


Fig. 5-39 SOC of battery in case 2 based on experiment results.

Case 3: High SOC and High Temperature

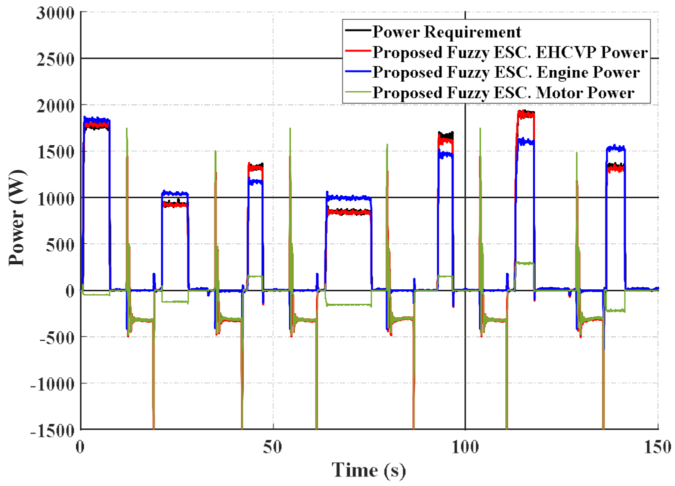


Fig. 5-40 Power allocation by using proposed Fuzzy ESC in case 3.

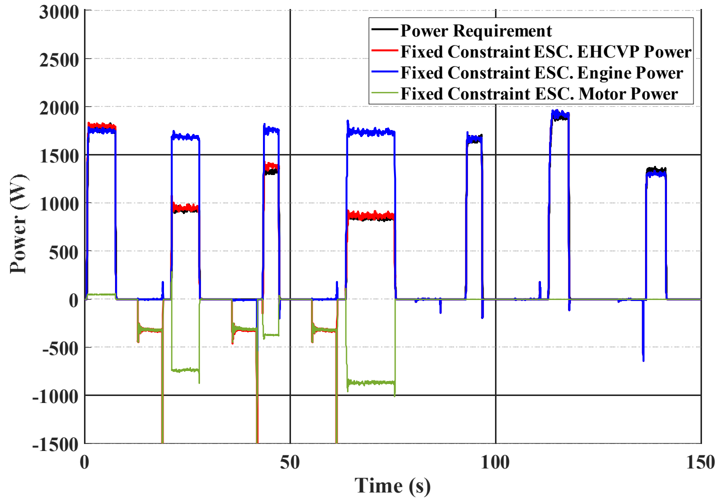


Fig. 5-41 Power allocation by using Fixed Constraint ESC in case 3.

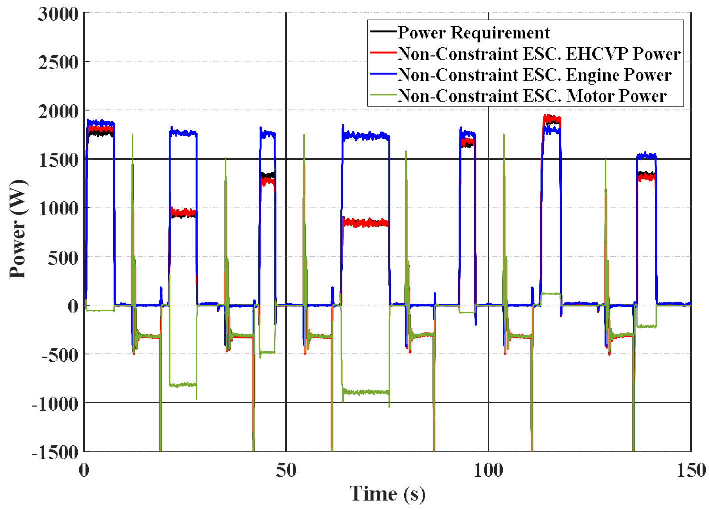


Fig. 5-42 Power allocation by using Non-Constraint ESC in case 3.

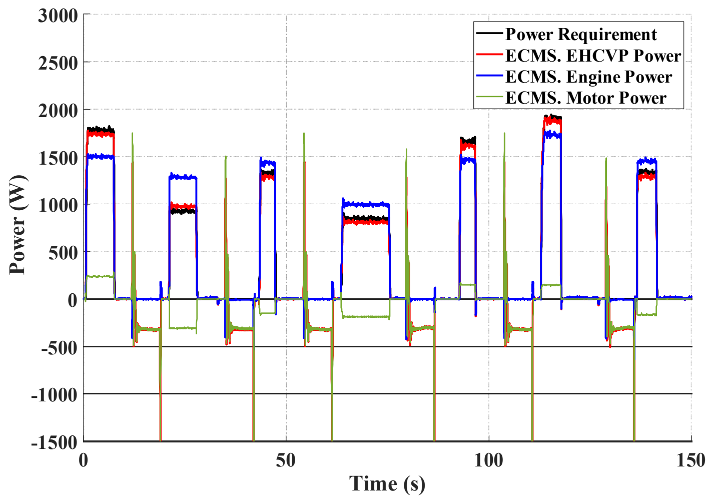


Fig. 5-43 Power allocation by using ECMS in case 3.

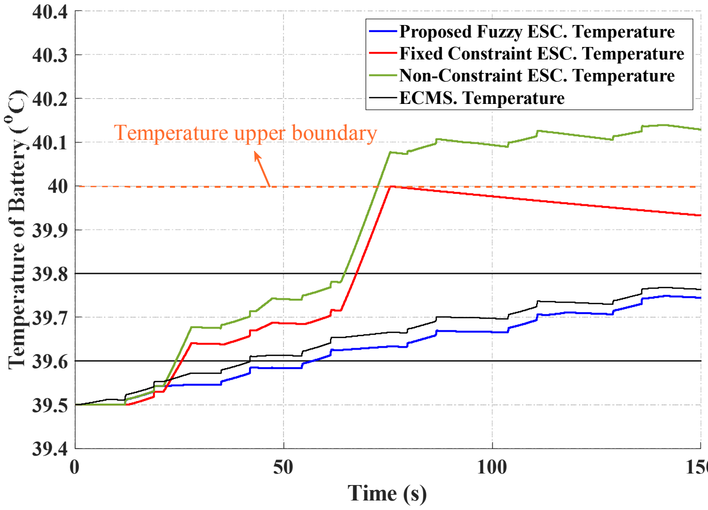


Fig. 5-44 Temperature of battery in case 3 based on experiment results.

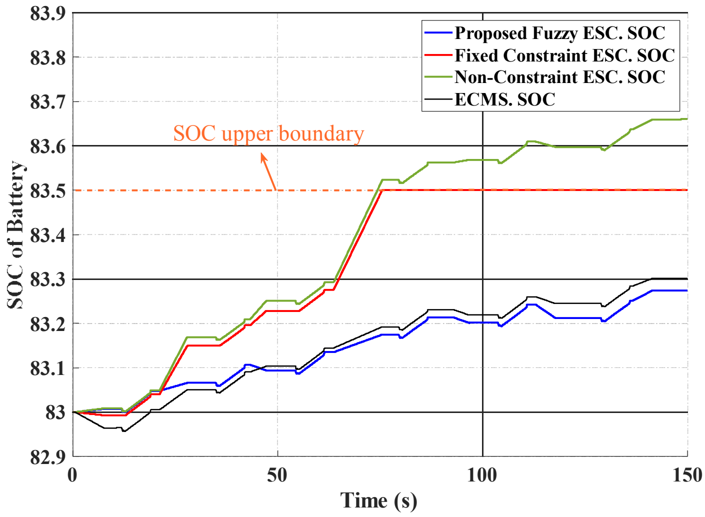


Fig. 5-45 SOC of battery in case 3 based on experiment results.

Case 4: Low SOC, Low Temperature, and High Current

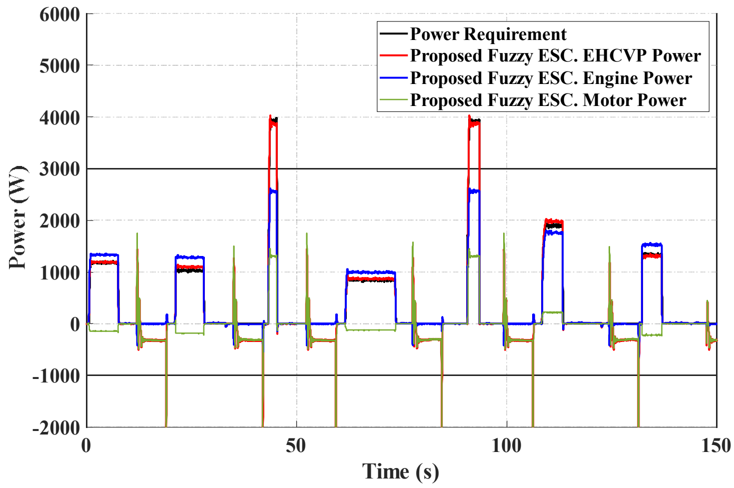


Fig. 5-46 Power allocation by using proposed Fuzzy ESC in case 4.

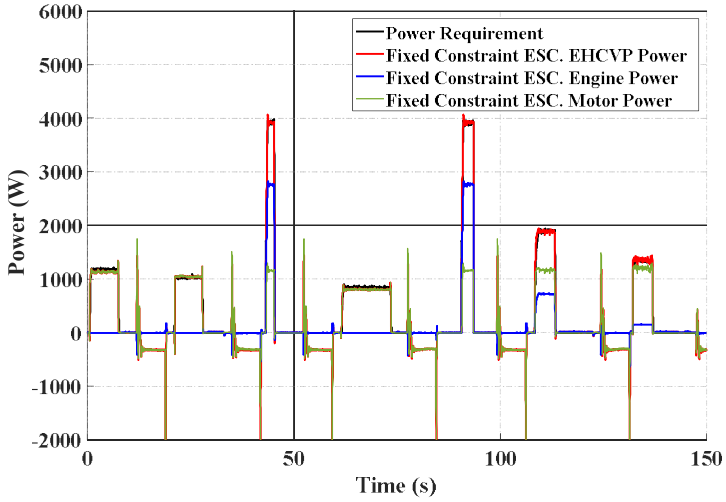


Fig. 5-47 Power allocation by using Fixed Constraint ESC in case 4.

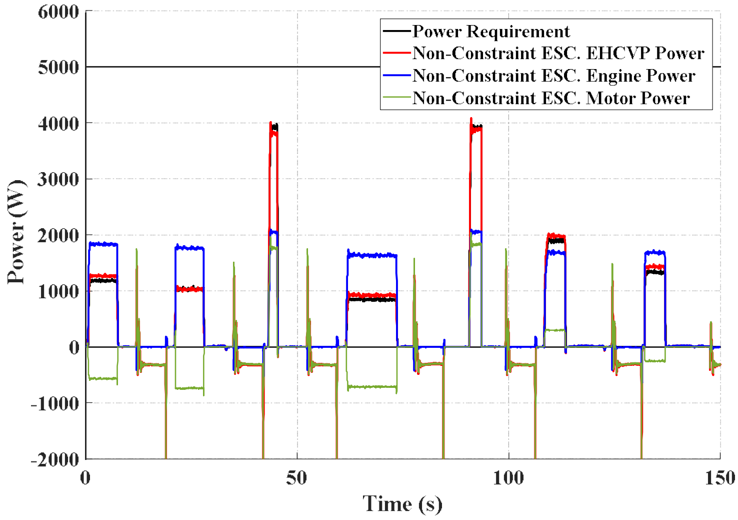


Fig. 5-48 Power allocation by using Non-Constraint ESC in case 4.

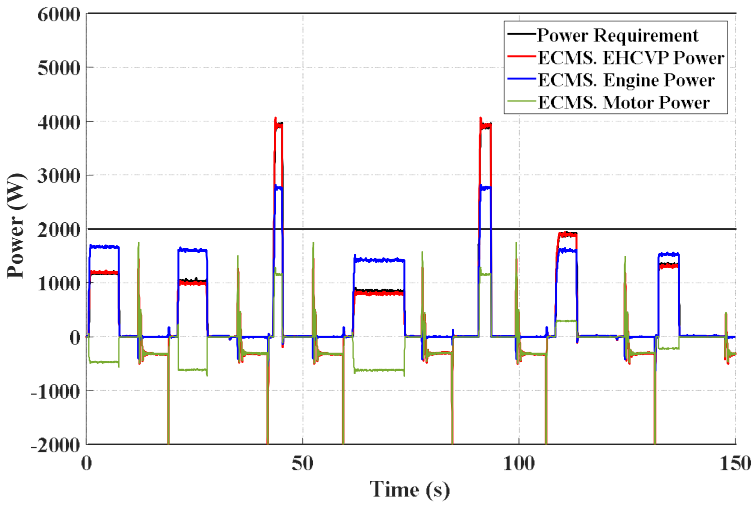


Fig. 5-49 Power allocation by using ECMS in case 4.

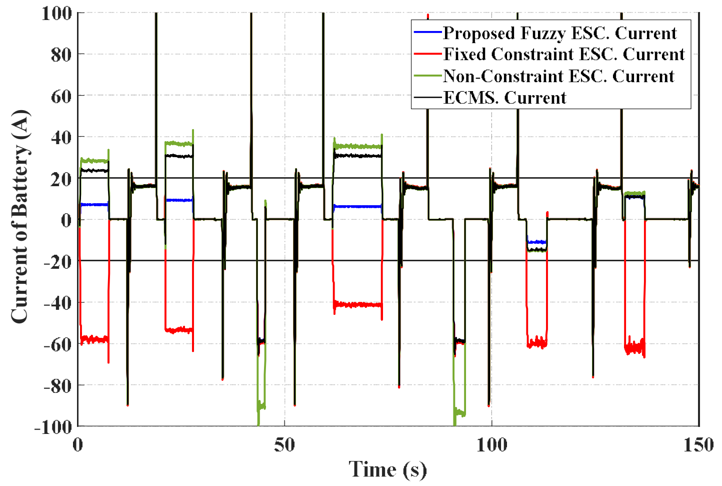


Fig. 5-50 Current of battery in case 4 based on experiment results.

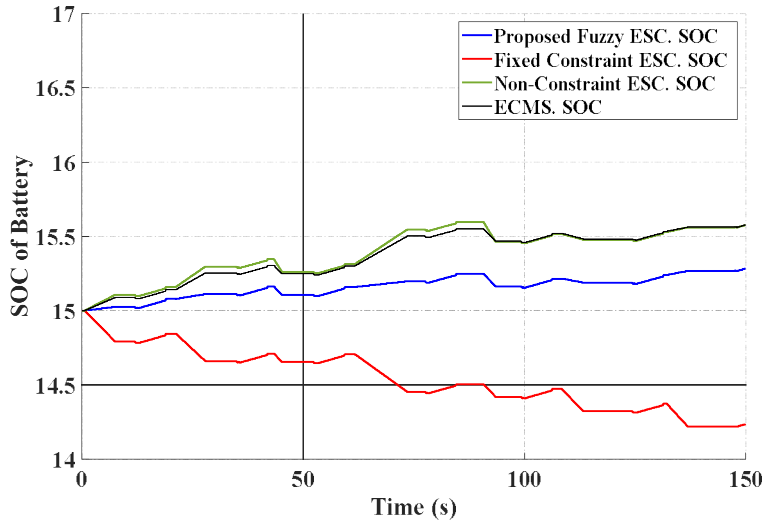


Fig. 5-51 SOC of battery in case 4 based on experiment results.

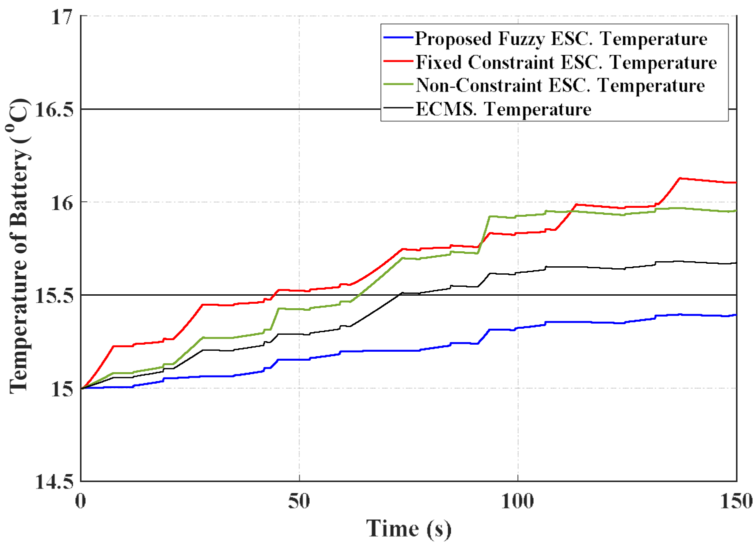


Fig. 5-52 Temperature of battery in case 4 based on experiment results.

Table 5-7 Summary table of constraint

Working Condition	ESC No Constraint	ESC Fix Constraint	Proposed ESC with Fuzzy Constraint	ECMS	Note
High Current	Cannot limit the maximum current → Dangerous with battery	Limit the current in the desired boundary	Limit the current in the desired boundary	Limit the current in the desired boundary	Indicated that without constraint the current cannot be guaranteed in the desired boundary
High SOC	Cannot limit the maximum SOC → Dangerous with battery	When the SOC reaches the upper limit, the engine suddenly turns off, and the motor changes, making the system unstable.	Not reach to the upper boundary of SOC	Not reach to the upper boundary of SOC	Indicated that the proposed control can guarantee the stability of the system
High SOC and high temperature	Cannot limit the maximum SOC, and temperature → Dangerous with battery	The required power is supplied by the motor → SOC can be reduced, and Temperature continuously increases → Dangerous with battery	When the SOC and temperature are high, the required power is supplied by the engine → the motor is stopped → protect the battery	Limit the temperature and SOC in their boundaries	Indicated that the proposed control can protect the battery when the SOC and Temperature are high
Low temperature, low SOC, and high current	Cannot limit the maximum current → Dangerous with battery	The required power is supplied by the motor → SOC cannot increase → Dangerous with battery	Increase the SOC and Temperature of the Battery, limit the maximum current	Increase the SOC and Temperature of the Battery, limit the maximum current	Indicated that the proposed control can increase the SOC and Temperature. Besides, the current can be limited

Table 5-8 Comparation table of experimental results of a 50000 cycles projection

Working Condition	Criteria	Non-Constraint ESC	Fixed Constraint ESC	Proposed Fuzzy ESC	ECMS
High Current	Power following error	6.8%	6.2%	5.4%	5.2%
	Energy Consumption	8533 MJ	8273 MJ (-3%)	7913MJ (-7.26%)	8060MJ (5.54%)
	Engine Efficiency	0.435	0.43	0.418	0.42
	State of Health	90.48%	91.8%	92.7%	92.53%
High SOC	Power following	6.9%	6.2%	4.8%	4.9%
	Energy Consumption	7356 MJ	6053 MJ (17.7%)	6315 MJ (14.15%)	6425 MJ (12.65%)
	Engine Efficiency	0.42	0.35	0.378	0.35
	State of Health	94.2%	92.9%	95.65%	95.5%
High SOC and high temperature	Power following	6.54%	6.83%	5.35%	5.25%
	Energy Consumption	7025 MJ	7335 MJ (+4.4%)	6434 MJ (-8.4%)	6502 MJ (-7.44%)
	Engine Efficiency	0.43	0.38	0.355	0.353
	State of Health	89.6%	91.59%	92.7%	92%

Low temperature, low SOC, and high current	Power following	6.5%	5.2%	5.4%	5.6%
	Energy Consumption	7211 MJ	3538 MJ (-50.9%)	6435 MJ (-10.76%)	6657 MJ (-7.68%)
	Engine Efficiency	0.425	0.27	0.373	0.382
	State of Health	93.6%	92.8%	95.3%	95.2%

Similar to the simulation model, four working conditions are also used to verify the performance of the experimental test bench (Figs 5-28 to 5-45). The results indicated that the power requirement is divided into the power source by using the proposed fuzzy. In which, the electric motor/generator compensates for the power of the ICE by changing the operating mode to keep the working point of the ICE in its high-efficiency region. Moreover, in the first case, the current of the battery can be limited in the defined working boundary to ensure the durability of the battery. In the second case with the high SOC condition, the proposed fuzzy ESC can reduce the charging power into the battery to avoid the SOC beyond the allowable threshold. Meanwhile, the fixed constraint can also limit the battery's SOC. However, supplying power entirely by the battery via the electric motor/generator to the hydraulic system leads to a rapid increase in temperature and current, thus reducing the battery lifespan. In the third case, the non-constraint ESC cannot keep the SOC and temperature in the boundary by only considering the efficiency of the ICE. This problem can overcome by the proposed fuzzy ESC with the capacity loss can be reduced by about 29.8% based on 50000 cycles projections. In the final case, the fixed constraint ESC continues to use power from the battery to supply to the system even if its SOC is at a low level according to the characteristic of the penalty function. By using the proposed fuzzy ESC, most of the required power is provided by the ICE to protect the battery. Finally, the experimental results are listed in Tables 5-7, 5-8 to compare the effectiveness of the proposed fuzzy ESC with other EMSs.

Although there are some differences between the experimental and simulation results due to nonlinear parameters such as mechanical frictions and hydraulic losses, the results express that the proposed EHCVP with fuzzy ESC can be operated with not only high performance but also ensures the battery lifespan.

5.5. Chapter Summary

This chapter presents an advanced energy management strategy for the hybrid hydraulic excavator to optimize energy regeneration and energy-saving capability. The EMS based on a combination between the ESC and fuzzy method was suggested to adaptively change the power reference of the ICE to ensure the safety and lifespan of devices. A co-simulation between AMESim and Matlab and a real test bench were built to validate the performance of the proposed system and EMS. Compared with the conventional EHCVP, the proposed EHCVP can improve energy saving and energy regeneration by up to 7% and 48.2%, respectively. Besides, by using the proposed EMS up to 3.35% of the battery health could be saved, leading to 33% improvement in capacity loss based on 50000 working cycle projections.

Chapter 6
CONCLUSION AND FUTURE WORKS

6.1. Conclusions

In this thesis, the EHCVP was proposed as a powertrain of the hydraulic excavator. In the EHCVP, the electric motor/generator can work as a motor or a generator to provide mechanical energy or generate electric energy. The speed of the engine and motor/generator decide the speed of the main pump through planetary gear. Then the engine speed can be controlled to the high-efficiency range with the EHCVP. A variable displacement pump was installed in the system to govern the torque of the engine. Hence, the engine working points can be controlled in the high-efficiency range. However, the maximum displacement of the hydraulic pump limits the controlled range of engine torque in the condition of a large velocity.

To enhance energy-saving efficiency, a two-speed gearbox is installed between the ring gear shaft and the hydraulic pump. The main pump was driven by the ICE and the electric motor/generator via a planetary gear allowed the working point of the ICE could be adjusted to a higher efficiency region under the same conditions. Besides, two double clutches were used, in which, the first one switched the driven or regeneration modes based on the operation status of the boom cylinder. The other one was integrated to adjust the gear ratio from the power sources to the hydraulic system to enhance the working efficiency of the ICE.

Furthermore, an advanced energy management strategy (EMS) based on an extremum-seeking method was proposed to switch the gear ratio and distribute the power requirement to each power source. A fuzzy logic system is designed based on consideration of the battery aging to adaptively change the power reference of the ICE to ensure the safety and lifespan of devices. A co-simulation between AMESim and Matlab and a real test bench were built to validate the performance of the proposed system and EMS.

The results showed that during operation, the working point of the ICE was kept in its high-efficiency region and the excess energy could be compensated by the electric motor/generator. In addition, the recoverable energy in the boom cylinder can be captured and stored in the battery with the energy regeneration efficiency could be reached to 48.2%. Compared with the conventional EHCVP, the proposed EHCVP can improve energy saving by about 7%. Besides, by using the proposed EMS up to 3.35% of the battery health could be saved, leading to 33% improvement in capacity loss based on 50000 working cycle projections.

6.2. Future works

However, it can be seen that the torque of the ICE should be adjusted according to different working conditions to achieve optimal efficiency. Therefore, in future work, a continuously variable transmission (CVT) will be used to adaptively adjust the gear ratio to enhance the efficiency of ICE. In the case of low load conditions, the CVT will be adjusted to a higher gear ratio to increase the torque of the engine. In the case of high load conditions, the CVT will be adjusted to a smaller gear ratio to reduce the torque and avoid damage to the engine.

With integrating the CVT into the EHCVP system, a control algorithm should be used to adaptively adjust the gear ratio to achieve optimal engine's efficiency and smoothly operate the system to avoid unstable situations.

Publish papers and patents

A. International Journal

1. **Do, T. C.**, Truong, H. V. A., Dao, H. V., Ho, C. M., To, X. D., Dang, T. D., & Ahn, K. K. "Energy management strategy of a PEM fuel cell excavator with a supercapacitor/battery hybrid power source". Energies, 2019, 12(22), 4362.
2. Tran, D. T., **Do, T. C.**, & Ahn, K. K. "Extended high gain observer-based sliding mode control for an electro-hydraulic system with a variant payload". International Journal of Precision Engineering and Manufacturing, 2019, 20(12), 2089-2100.
3. Truong, H. V. A., Dao, H. V., **Do, T. C.**, Ho, C. M., To, X. D., Dang, T. D., & Ahn, K. K. "Mapping fuzzy energy management strategy for PEM Fuel Cell–Battery–Supercapacitor hybrid excavator". Energies, 2020, 13(13), 3387.
4. **Do, T. C.**, Tran, D. T., Dinh, T. Q., & Ahn, K. K. "Tracking control for an Electro-hydraulic rotary actuator using fractional order fuzzy PID controller". Electronics, 2020, 9(6), 926.
5. **Do, T. C.**, Nguyen, D. G., Dang, T. D., & Ahn, K. K. "A Boom Energy Regeneration System of Hybrid Hydraulic Excavator Using Energy Conversion Components". Actuators, 2020, 10(1),1.
6. Dao, H. V., To, X. D., Truong, H. V. A., **Do, T. C.**, Ho, C. M., Dang, T. D., & Ahn, K. K. "Optimization-Based Fuzzy Energy Management Strategy for PEM Fuel Cell/Battery/Supercapacitor Hybrid Construction Excavator". International Journal of Precision Engineering and Manufacturing-Green Technology, 2021, 8(4), 1267-1285.
7. **Do, T. C.**, Dang, T. D., Dinh, T. Q., & Ahn, K. K. "Developments in energy regeneration technologies for hydraulic excavators: A review". Renewable and Sustainable Energy Reviews, 2021, 145, 111076.
8. **Do, T. C.**, Dang, T. D., & Ahn, K. K. "Efficiency Improvement of a Hydraulic Power Take-off of Wave Energy Converter Using Variable Displacement Motor". International Journal of Precision Engineering and Manufacturing-Green Technology, 2021, 1-13.
9. Dang, T. D., **Do, T. C.**, & Ahn, K. K. "Experimental assessment of the power conversion of a wave energy converter using hydraulic power take-off mechanism". International Journal of Precision Engineering and Manufacturing-Green Technology, 2021, 8(5), 1515-1527.
10. Yu, Y., **Do, T. C.**, Park, Y., & Ahn, K. K. "Energy saving of hybrid hydraulic excavator with innovative powertrain". Energy Conversion and Management, 2021, 244, 114447.

11. Nguyen, T. H., **Do, T. C.**, & Ahn, K. K. “A Study on a New Independent Metering Valve for Hydraulic Boom Excavator”. Applied Sciences, 2022, 12(2), 605.

12. Trinh, H. A., Truong, H. V. A., **Do, T. C.**, Nguyen, M. H., & Ahn, K. K. “Optimization-based energy management strategies for hybrid construction machinery: A review”. Energy Reports, 2022, 8, 6035-6057.

13. Yu, Y., **Do, T. C.**, Yin, B., & Ahn, K. K. “Improvement of Energy Saving for Hybrid Hydraulic Excavator with Novel Powertrain”. International Journal of Precision Engineering and Manufacturing-Green Technology, 2022, 1-14.

14. Dang, T. D., **Do, T. C.**, & Ahn, K. K. “Design and experiment of a direct-drive wave energy converter using a variable stiffness mechanism”. Ocean Engineering, 2022, 266, 112841.

15. Nguyen, T. H., **Do, T. C.**, Nguyen, V. H., & Ahn, K. K. “High Tracking Control for a New Independent Metering Valve System Using Velocity-Load Feedforward and Position Feedback Methods”. Applied Sciences, 2022, 12(19), 9827.

16. Trinh, H. A., Truong, H. V. A., Pham, M. D., **Do, T. C.**, Lee, H. H., & Ahn, K. K. “Comprehensive Control Strategy and Verification for PEM Fuel Cell/Battery/Supercapacitor Hybrid Power Source”. International Journal of Precision Engineering and Manufacturing-Green Technology, 2022, Accepted, Article in Press.

B. KCI journal

17. Dinh, T. X., Thuy, L. K., Tien, N. T., Dang, T. D., Ho, C. M., Truong, H. V. A., Dao, H. V., **Do, T. C.**, & Ahn, K. K. “Modeling and energy management strategy in energetic macroscopic representation for a fuel cell hybrid electric vehicle”. Journal of Drive and Control, 2019, 16(2), 80-90.

18. Dang, T. D., **Do, T. C.**, Truong, H. V. A., Ho, C. M., Dao, H. V., Xiao, Y. Y., Joeng, E. J., & Ahn, K. K. “Design, modeling and analysis of a PEM fuel cell excavator with supercapacitor/battery hybrid power source”. Journal of Drive and Control, 2019, 16(1), 45-53.

19. Park, Y. S., Yu, Y. X., Yun, J. S., **Do, T. C.**, Han, S. M., Shin, J. W., Yu. C. W., & Ahn, K. K. “A Study on the Regeneration Efficiency of the Electric Forklift Using the Variable Hydraulic Motor”. Journal of Drive and Control, 2020, 17(3), 26-32.

20. Nguyen, T. H., **Do, T. C.**, & Ahn, K. K. “Independent Metering Valve: A Review of Advances in Hydraulic Machinery”. Journal of Drive and Control, 2020, 17(4), 54-71.

B. International Conference

21. **Do, T. C.**, Jeong, E. J., & Ahn, K. K. "Research on the Energy Regeneration Systems for Hybrid Hydraulic Excavators". Korean Society for Fluid Power Conference, 2018, 137-141.

22. **Do, T. C.**, Tran, D. T., & Ahn, K. K. "Fractional order fuzzy PID controller for an electro-hydraulic rotary actuator". 23rd International Conference on Mechatronics Technology. 2019, 1-6.

23. Dang, T. D., **Do, T. C.**, & Ahn, K. K. "Direct Drive Wave Energy Converter with Variable Stiffness Structure". AFORE, 2019, 59-59.

24. Nguyen, T. H., **Do, T. C.**, & Ahn, K. K. "Research on a New Independent Metering System for Boom Excavator". 24th International Conference on Mechatronics Technology. 2021, 1-5.

C. Patents

25. Ahn, K. K, Truong, H. V. A., Dang, T. D., **Do, T. C.**, and Dao, H. V., "Power Management Control Method of Vehicle Having Multi Power Source". Korean Patent, 1021536260000 (2020.09.02).

26. Ahn, K. K, **Do, T. C.**, Dang, T. D., and Jeong, E. J., A Polymer Electrolyte Membrane Fuel Cell Forklift with Energy Regeneration Function. Korean Patent, 1021988300000 (2020.12.29).

27. Ahn, K. K, Truong, H. V. A., Dang, T. D., S. Y., and **Do, T. C.**, "Hydrogen Generation System Using Seawater and Renewable Energy". Korean Patent, 1022412720000 (2021.04.12).

28. Ahn, K. K, Hwang, J. W., Kim, I., **Do, T. C.**, "Calculation Method of Circular Tooth Profile of Silenced Gear Pump and Gear Calculated by The Same". Korean Patent, 1022846620000 (2021.07.27).

29. Ahn, K. K, **Do, T. C.**, Truong, H. V. A., "Continuously Variable Powertrain with Integrated Hydraulic Flywheel to Saver Energy In The Boom System". Korean Patent, 1022846620000 (2022.06.02).

References

[1] IEA, "Total final consumption (TFC) by source," *IEA,* vol. https://www.iea.org/data-and-statistics, 2017.

[2] D. Q. Truong, J. Marco, D. Greenwood, L. Harper, D. G. Corrochano, and J. I. Yoon, "Challenges of micro/mild hybridisation for construction machinery and applicability in UK," *Renewable and Sustainable Energy Reviews,* vol. 91, pp. 301-320, 2018, doi: 10.1016/j.rser.2018.03.027.

[3] H. Wang, Q. Wang, and B. Hu, "A review of developments in energy storage systems for hybrid excavators," *Automation in Construction,* vol. 80, pp. 1-10, 2017, doi: 10.1016/j.autcon.2017.03.010.

[4] H. Kim, S. Yoo, S. Cho, and K. Yi, "Hybrid control algorithm for fuel consumption of a compound hybrid excavator," *Automation in Construction,* vol. 68, pp. 1-10, 2016, doi: 10.1016/j.autcon.2016.03.017.

[5] P. Casoli, A. Gambarotta, N. Pompini, and L. Riccò, "Hybridization methodology based on DP algorithm for hydraulic mobile machinery — Application to a middle size excavator," *Automation in Construction,* vol. 61, pp. 42-57, 2016, doi: 10.1016/j.autcon.2015.09.012.

[6] J. Kim and S. Chi, "Action recognition of earthmoving excavators based on sequential pattern analysis of visual features and operation cycles," *Automation in Construction,* vol. 104, pp. 255-264, 2019, doi: 10.1016/j.autcon.2019.03.025.

[7] P. Casoli, A. Gambarotta, N. Pompini, and L. Riccò, "Coupling excavator hydraulic system and internal combustion engine models for the real-time simulation," *Control Engineering Practice,* vol. 41, pp. 26-37, 2015, doi: 10.1016/j.conengprac.2015.04.003.

[8] T. Wang and Q. Wang, "Efficiency analysis and evaluation of energy-saving pressure-compensated circuit for hybrid hydraulic excavator," *Automation in Construction,* vol. 47, pp. 62-68, 2014, doi: 10.1016/j.autcon.2014.07.012.

[9] IEA, "CO2 emissions by energy source," *IEA,* vol. https://www.iea.org/data-and-statistics, 2017.

[10] M. Vukovic, R. Leifeld, and H. Murrenhoff, "Reducing Fuel Consumption in Hydraulic Excavators—A Comprehensive Analysis," *Energies,* vol. 10, no. 5, 2017, doi: 10.3390/en10050687.

[11] R. C. Winck, M. Elton, and W. J. Book, "A practical interface for coordinated position control of an excavator arm," *Automation in Construction,* vol. 51, pp. 46-58, 2015, doi: 10.1016/j.autcon.2014.12.012.

[12] F. A. Bender, M. Mitschke, T. Bräunl, and O. Sawodny, "Predictive operator modeling for virtual prototyping of hydraulic excavators," *Automation in Construction,* vol. 84, pp. 133-145, 2017, doi: 10.1016/j.autcon.2017.08.008.

[13] Q. H. Le, J. W. Lee, and S. Y. Yang, "Remote control of excavator using head tracking and flexible monitoring method," *Automation in Construction,* vol. 81, pp. 99-111, 2017, doi: 10.1016/j.autcon.2017.06.015.

[14] D. Wang, L. Zheng, H. Yu, W. Zhou, and L. Shao, "Robotic excavator motion control using a nonlinear proportional-integral controller and cross-coupled pre-compensation," *Automation in Construction,* vol. 64, pp. 1-6, 2016, doi: 10.1016/j.autcon.2015.12.024.

[15] T. Lin, Q. Chen, H. Ren, W. Huang, Q. Chen, and S. Fu, "Review of boom potential energy regeneration technology for hydraulic construction machinery," *Renewable and Sustainable Energy Reviews,* vol. 79, pp. 358-371, 2017, doi: 10.1016/j.rser.2017.05.131.

[16] T. Lin, Q. Wang, B. Hu, and W. Gong, "Development of hybrid powered hydraulic construction machinery," *Automation in Construction,* vol. 19, no. 1, pp. 11-19, 2010, doi: 10.1016/j.autcon.2009.09.005.

[17] T. C. Do, T. D. Dang, T. Q. Dinh, and K. K. Ahn, "Developments in energy regeneration technologies for hydraulic excavators: A review," *Renewable and Sustainable Energy Reviews,* vol. 145, 2021, doi: 10.1016/j.rser.2021.111076.

[18] M. Kagoshima, M. Komiyama, T. Nanjo, and A. Tsutsui, "Development of new hybrid excavator," *Kobelco Technology Review,* vol. 27, pp. 39-42, 04/01 2007.

[19] H. Wang and Q. Wang, "Parameter matching and control of series hybrid hydraulic excavator based on electro-hydraulic composite energy storage," *IEEE Access,* vol. 8, pp. 111899-111912, 2020.

[20] D. Wang, X. Lin, and Y. Zhang, "Fuzzy logic control for a parallel hybrid hydraulic excavator using genetic algorithm," *Automation in Construction,* vol. 20, no. 5, pp. 581-587, 2011, doi: 10.1016/j.autcon.2010.11.024.

[21] H. Inoue, "Introduction of PC200-8 Hybrid Hydraulic Excavators," *Komatsu technical report,* vol. Vol. 54 No.161, 2008.

[22] K. Tae-Suk *et al.*, "Power Control Algorithm for Hybrid Excavator With Supercapacitor," *IEEE Transactions on Industry Applications,* vol. 46, no. 4, pp. 1447-1455, 2010, doi: 10.1109/tia.2010.2049815.

[23] T. C. Do, D. G. Nguyen, T. D. Dang, and K. K. Ahn, "A Boom Energy Regeneration System of Hybrid Hydraulic Excavator Using Energy Conversion Components," in *Actuators*, 2021, vol. 10, no. 1: Multidisciplinary Digital Publishing Institute, p. 1.

[24] Y.-X. Yu and K. K. Ahn, "Energy Regeneration and Reuse of Excavator Swing System with Hydraulic Accumulator," *International Journal of Precision Engineering and Manufacturing-Green Technology,* 2019, doi: 10.1007/s40684-019-00157-7.

[25] Y.-X. Yu and K. K. Ahn, "Improvement of Energy Regeneration for Hydraulic Excavator Swing System," *International Journal of Precision Engineering and Manufacturing-Green Technology,* vol. 7, no. 1, pp. 53-67, 2019, doi: 10.1007/s40684-019-00165-7.

[26] L. Ge, Z. Dong, L. Quan, and Y. Li, "Potential energy regeneration method and its engineering applications in large-scale excavators," *Energy Conversion and Management,* vol. 195, pp. 1309-1318, 2019, doi: 10.1016/j.enconman.2019.05.079.

[27] M. Chen and D. Zhao, "The gravitational potential energy regeneration system with closed-circuit of boom of hydraulic excavator," *Mechanical Systems and Signal Processing,* vol. 82, pp. 178-192, 2017, doi: 10.1016/j.ymssp.2016.05.017.

[28] Y.-X. Yu and K. K. Ahn, "Optimization of energy regeneration of hybrid hydraulic excavator boom system," *Energy Conversion and Management,* vol. 183, pp. 26-34, 2019, doi: 10.1016/j.enconman.2018.12.084.

[29] Q. Chen, T. Lin, H. Ren, and S. Fu, "Novel potential energy regeneration systems for hybrid hydraulic excavators," *Mathematics and Computers in Simulation,* vol. 163, pp. 130-145, 2019, doi: 10.1016/j.matcom.2019.02.017.

[30] T. Lin, W. Huang, H. Ren, S. Fu, and Q. Liu, "New compound energy regeneration system and control strategy for hybrid hydraulic excavators," *Automation in Construction,* vol. 68, pp. 11-20, 2016, doi: 10.1016/j.autcon.2016.03.016.

[31] T. Do, E. Jeong, and K. Ahn, "Research on the Energy Regeneration Systems for Hybrid Hydraulic Excavators," *KSFC Conference* pp. 137-141, 2018.

[32] R. Schmid, J. Bürger, and N. Bajcinca, "A comparison of PMP-based energy management strategies for plug-in-hybrid electric vehicles," *IFAC-PapersOnLine,* vol. 52, no. 5, pp. 592-597, 2019.

[33] C. S. Teodorescu *et al.*, "An ECMS-based powertrain control of a parallel hybrid electric forklift," in *2017 21st International Conference on System Theory, Control and Computing (ICSTCC)*, 2017: IEEE, pp. 763-770.

[34] A. Fröberg, J. Åslund, and L. Nielsen, "Optimal transient control of power generation in hybrid construction equipment," in *2011 IEEE Vehicle Power and Propulsion Conference*, 2011: IEEE, pp. 1-6.

[35] Y. Wang and Z. Sun, "SDP-based extremum seeking energy management strategy for a power-split hybrid electric vehicle," in *2012 American Control Conference (ACC)*, 2012: IEEE, pp. 553-558.

[36] H. Inoue, "Introduction of PC200-8 hybrid hydraulic excavators," *Komatsu Technical Report,* vol. 54, pp. 1-6, 01/01 2008.

[37] M. Kagoshima, "Development of 8 tonne class hybrid hydraulic excavator SK80H," vol. 62, pp. 14-18, 08/01 2012.

[38] K. Ishida and M. Higurashi, "Hybrid wheel loaders incorporating power electronics," vol. 64, pp. 398-402, 08/01 2015.

[39] A. Soma, "Trends and Hybridization Factor for Heavy-Duty Working Vehicles," 2017, pp. 3-32.

[40] B. S. Pablo Castro Palavicino, Dheeraj Bobba, Woongkul Lee, Tatiana, Minav, "Electrification of hydraulic systems using highefficiency permament magnet motors," *12th International Fluid Power Conference (12. IFK). Dresden, October 12 – 14, 2020,* vol. Volume 1 – Symposium - 1, 2020.

[41] T. Lin, Y. Lin, H. Ren, H. Chen, Q. Chen, and Z. Li, "Development and key technologies of pure electric construction machinery," *Renewable and Sustainable Energy Reviews,* vol. 132, p. 110080, 2020/10/01/ 2020, doi: https://doi.org/10.1016/j.rser.2020.110080.

[42] M. Ochiai, "Development for environment friendly construction machinery," *Construction,* vol. 9, pp. 24-28, 2003.

[43] D. Arsić, N. Gnjatović, S. Sedmak, A. Arsić, and M. Uhričik, "Integrity assessment and determination of residual fatigue life of vital parts of bucket-wheel excavator operating under dynamic loads," *Engineering Failure Analysis,* vol. 105, pp. 182-195, 2019, doi: 10.1016/j.engfailanal.2019.06.072.

[44] Y. Shi, Y. Xia, Y. Zhang, and Z. Yao, "Intelligent identification for working-cycle stages of excavator based on main pump pressure," *Automation in Construction,* vol. 109, 2020, doi: 10.1016/j.autcon.2019.102991.

[45] I. Cireş and V.-M. Nani, "Stability control for a huge excavator for surface excavation," *Applied Mathematical Modelling,* vol. 40, no. 1, pp. 388-397, 2016, doi: 10.1016/j.apm.2015.04.056.

[46] Y. D. Kanezawa, Y.; Kawaguchi, T, "Increasing efficiency of construction machine by hybrid system," *In Proceedings of the JSAE (Society of Automotive Engineers of Japan) Annual Congress, Tokyo, Japan,* 2001.

[47] Q. Xiao, Q. Wang, and Y. Zhang, "Control strategies of power system in hybrid hydraulic excavator," *Automation in Construction,* vol. 17, no. 4, pp. 361-367, 2008, doi: 10.1016/j.autcon.2007.05.014.

[48] T. Wang, Q. Wang, and T. Lin, "Improvement of boom control performance for hybrid hydraulic excavator with potential energy recovery," *Automation in Construction,* vol. 30, pp. 161-169, 2013, doi: 10.1016/j.autcon.2012.11.034.

[49] T. Wang and Q. Wang, "Design and analysis of compound potential energy regeneration system for hybrid hydraulic excavator," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering,* vol. 226, no. 10, pp. 1323-1334, 2012, doi: 10.1177/0959651812456642.

[50] A. K. K. Jong Il Yoon, Dinh Quang Truong, "A Study on An Energy Saving Electro-Hydraulic Excavator," *ICROS-SICE International Joint Conference 2009,* 2009.

[51] J. I. Yoon, D. Q. Truong, and K. K. Ahn, "A generation step for an electric excavator with a control strategy and verifications of energy consumption," *International Journal of Precision Engineering and Manufacturing,* vol. 14, no. 5, pp. 755-766, 2013, doi: 10.1007/s12541-013-0099-6.

[52] D. Q. T. Bui Ngoc Minh Truong, Lee Se Young, Lee So Young, Ahn Kyoung Kwan, "Study on Energy Regeneration System for Hybrid Hydraulic Excavator," presented at the International Conference on Fluid Power and Mechatronics, 2015.

[53] M. L. Knussman, P. Opdenbosch, and J. Dierking, "Closed-loop hydraulic system having regeneration configuration," ed: US Patents, 2015.

[54] O. O. Puja Chowdhuryi, Truong B. N. M, KyoungKwan Ahn, "Research on Energy Regeneration and Effect of Dynamic Characteristics of Secondary Control Swing for Hydraulic Excavator System," presented at the International Conference on Control, Automation and Systems, 2015.

[55] L. Ge, L. Quan, Y. Li, X. Zhang, and J. Yang, "A novel hydraulic excavator boom driving system with high efficiency and potential energy regeneration capability," *Energy Conversion and Management,* vol. 166, pp. 308-317, 2018, doi: 10.1016/j.enconman.2018.04.046.

[56] K. Rongjie, J. Zongxia, W. Shaoping, and C. Lisha, "Design and Simulation of Electro-hydrostatic Actuator with a Built-in Power Regulator," *Chinese Journal of Aeronautics,* vol. 22, no. 6, pp. 700-706, 2009, doi: 10.1016/s1000-9361(08)60161-2.

[57] L. Ge, L. Quan, X. Zhang, B. Zhao, and J. Yang, "Efficiency improvement and evaluation of electric hydraulic excavator with speed and displacement variable pump," *Energy Conversion and Management,* vol. 150, pp. 62-71, 2017, doi: 10.1016/j.enconman.2017.08.010.

[58] T. Lin, Q. Wang, B. Hu, and W. Gong, "Research on the energy regeneration systems for hybrid hydraulic excavators," *Automation in Construction,* vol. 19, no. 8, pp. 1016-1026, 2010, doi: 10.1016/j.autcon.2010.08.002.

[59] J. Zhang, P. Ma, T. Shang, G. V. Wen, B. E. Nelson, and D. Chen, "Electro-hydraulic system for recovering and reusing potential energy," ed: US Patents, 2016.

[60] J. D. Zimmerman, "Hydraulic hybrid circuit with energy storage for excavators or other heavy equipment," ed: US Patents, 2017.

[61] W. Shen, J. Jiang, X. Su, and H. Reza Karimi, "Control strategy analysis of the hydraulic hybrid excavator," *Journal of the Franklin Institute,* vol. 352, no. 2, pp. 541-561, 2015, doi: 10.1016/j.jfranklin.2014.04.007.

[62] J. Liu, Z. Jiao, F. Xian, and W. Liu, "Energy recovery and utilization system of excavator boom based on flow regeneration and balance theory," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* vol. 42, no. 1, 2019, doi: 10.1007/s40430-019-2124-x.

[63] L. Xia, L. Quan, L. Ge, and Y. Hao, "Energy efficiency analysis of integrated drive and energy recuperation system for hydraulic excavator boom," *Energy Conversion and Management,* vol. 156, pp. 680-687, 2018, doi: 10.1016/j.enconman.2017.11.074.

[64] T. V. X Liang, "An energy recovery system for a hydraulic crane," *Proc Instn Mech Engrs,* vol. Vol 215, C, 2001.

[65] L. S. Bruun, "Developed energy saving system in Caterpillars excavators," *Fluid Scand,* vol. 2, pp. 6-9, 2002.

[66] T. Minav, H. Hänninen, A. Sinkkonen, L. Laurila, and J. Pyrhönen, "Electric or Hydraulic Energy Recovery Systems in a Reach Truck– A Comparison," *Strojniški vestnik – Journal of Mechanical Engineering,* vol. 60, no. 4, pp. 232-240, 2014, doi: 10.5545/sv-jme.2013.1581.

[67] H. Zhou, P.-Y. Zhao, Y.-L. Chen, and H.-Y. Yang, "Prediction-based stochastic dynamic programming control for excavator," *Automation in Construction,* vol. 83, pp. 68-77, 2017, doi: 10.1016/j.autcon.2017.08.014.

[68] K.-K. A. Ying-Xiao Yu, "Study on Novel Structure and Control of Energy Saving of Hydraulic Hybrid Excavator," presented at the International Conference on Control, Automation and Systems, 2017.

[69] T. M. Shuzhong Zhang, and Matti Pietola, "Decentralized Hydraulics for Micro Excavator," presented at the The 15th Scandinavian International Conference on Fluid Power, Linköping, Sweden, 2017.

[70] P. Ranjan, G. Wrat, M. Bhola, S. K. Mishra, and J. Das, "A novel approach for the energy recovery and position control of a hybrid hydraulic excavator," *ISA Trans,* Sep 4 2019, doi: 10.1016/j.isatra.2019.08.066.

[71] J. Li, J. Zhao, and X. Zhang, "A Novel Energy Recovery System Integrating Flywheel and Flow Regeneration for a Hydraulic Excavator Boom System," *Energies,* vol. 13, no. 2, 2020, doi: 10.3390/en13020315.

[72] T. B. N. M. Se-Young Lee, Kyoung-Kwan Ahn, "Study on Energy Recuperation for Swing Motion in Electro-Hydraulic Excavator," presented at the International Conference on Control, Automation and Systems, 2015.

[73] J. Zhang, P. Ma, M. R. Schwab, T. Shang, and K. N. Patel, "Control system for recovering swing motor kinetic energy," ed: European Patent, 2011.

[74] J. Zhang, T. Shang, P. Spring, P. Ma, and R. N. Peterson, "Hydraulic control system having swing motor energy recovery," ed: Google Patents, 2014.

[75] Z. Ting and H. Yuan-cheng, "Simulation of hydraulic excavators slewing system based on hydraulic accumulator," in *2015 International Conference on Fluid Power and Mechatronics (FPM)*, 2015: IEEE, pp. 1063-1066.

[76] L. .Zhang, W. Fu, X. Yuan, and Z. Meng, "Research on Optimal Control of Excavator Negative Control Swing System," *Processes,* vol. 8, no. 9, 2020, doi: 10.3390/pr8091096.

[77] S.-g. Kim and J.-h. Kim, "Swing relief energy regeneration apparatus of an excavator," ed: US Patents, 2014.

[78] H. Ren, T. Lin, W. Huang, S. Fu, and Q. Chen, "Characteristics of the energy regeneration and reutilization system during the acceleration stage of the swing process of a hydraulic excavator," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 231, no. 6, pp. 842-856, 2016, doi: 10.1177/0954407016670275.

[79] Y. Y. Y. Lin Tianliang, Fu Shen Jie, Liu Qiang, "Energy-saving System of Swing for Hydraulic Excavators Based on Electric Energy Recovery Technology," *China Journal of Highway and Transport,* vol. 27, no. 8, 2014.

[80] K. K. Ahn, T. H. Ho, and Q. T. Dinh, "A study on energy saving potential of hydraulic control system using switching type closed loop constant pressure system," in *Proceedings of the JFPS International Symposium on Fluid Power*, 2008, vol. 2008, no. 7-2: The Japan Fluid Power System Society, pp. 317-322.

[81] D. Wang, C. Guan, S. Pan, M. Zhang, and X. Lin, "Performance analysis of hydraulic excavator powertrain hybridization," *Automation in Construction,* vol. 18, no. 3, pp. 249-257, 2009, doi: 10.1016/j.autcon.2008.10.001.

[82] D. D. Ying-Xiao Yu, Truong B. N. M, and Ahn Kyoung Kwan, "A Study on the Energy Regeneration System of Boom for Hybrid Hydraulic Excavator," presented at the International Conference on Control, Automation and Systems 2015.

[83] T. A. Minav, A. Virtanen, L. Laurila, and J. Pyrhönen, "Storage of energy recovered from an industrial forklift," *Automation in Construction,* vol. 22, pp. 506-515, 2012, doi: 10.1016/j.autcon.2011.11.010.

[84] Y. Hao, L. Quan, H. Cheng, L. Xia, L. Ge, and B. Zhao, "Potential energy directly conversion and utilization methods used for heavy duty lifting machinery," *Energy,* vol. 155, pp. 242-251, 2018.

[85] H. Huang, X. Zou, L. Li, X. Li, and Z. Liu, "Energy-saving design method for hydraulic press drive system with multi motor-pumps," *International Journal of Precision Engineering and Manufacturing-Green Technology,* vol. 6, no. 2, pp. 223-234, 2019.

[86] Y. Yu, T. C. Do, Y. Park, and K. K. Ahn, "Energy saving of hybrid hydraulic excavator with innovative powertrain," *Energy Conversion and Management,* vol. 244, 2021, doi: 10.1016/j.enconman.2021.114447.

[87] J. Wu, X. Wang, L. Li, and Y. Du, "Hierarchical control strategy with battery aging consideration for hybrid electric vehicle regenerative braking control," *Energy,* vol. 145, pp. 301-312, 2018.

[88] D. Zhou, A. Al-Durra, I. Matraji, A. Ravey, and F. Gao, "Online energy management strategy of fuel cell hybrid electric vehicles: a fractional-order extremum seeking method," *IEEE Transactions on Industrial Electronics,* vol. 65, no. 8, pp. 6787-6799, 2018.