Review

Developments in energy regeneration technologies for hydraulic excavators: a review

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Abstract: Construction machinery, especially hydraulic excavators, plays an important role in building and other industries. However, they often consume a lot of energy and emit large amounts of harmful emissions into the environment. This study focuses on energy regeneration technologies which can help reduce energy consumption and pollution in hydraulic excavators. First, potential recoverable energy sources in excavator mechanisms are analyzed. Next, energy regeneration systems are classified according to energy storage devices and their development is comprehensively reviewed through the state-of-art. The research gaps, market opportunities and future development directions of energy regeneration systems are discussed to underpin future development opportunities. A new conceptual design of ERS has been proposed to improve the energy regeneration efficiency whilst minimising the power consumption of hydraulic excavators.

Keywords: Hydraulic excavator; energy regeneration; electric system; hydraulic system.

1. Introduction

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 Figure 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 CO2 emissions in 2017 also increased 1.5 times compared to 1990 and the number increased steadily over the years as shown in Figure 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.

In the HEs, there are some places where energy can be recovered and reused [10-13]. In the boom system, when the boom cylinder moves down, the gravitational force can make the arm automatically go down without requiring additional power from the pump [14-16]. During this operation, the potential energy in the bore chamber consumes and generates the heat in the flow control valve, the excess energy directly goes to the tank. Meanwhile in the swing system, the energy generated by the hydraulic motor is completely recoverable for using in subsequent cycles. To take advantage of these recoverable energy sources, many energy regeneration approaches have been proposed. This research therefore aims to carry out a comprehensive review of the current state-of-art of energy regeneration technologies in hydraulic excavators as well as to recommend future development directions. The key contributions of this work can be expressed as follows:

- The latest technologies of energy recovery systems (ERS) employed in boom and swing systems to harvest potential energy and kinetic energy (during both the swing acceleration and deceleration), respectively, are studied and analyzed.
- The technologies are classified based on types of storage components. Comparison of between ERS from multiple perspectives, including energy regeneration efficiency, energy saving capacity, cost and complexity, are given.
- Research gaps, market opportunities and future development directions of ERSs are discussed to identify future development opportunities.
- A new conceptual design of an ERS to improve the energy regeneration efficiency whilst minimising the power consumption of boom system and swing systems is also introduced.

The rest of this paper is organized as follows: Section 2 presents potential sources of recoverable energy in the HE. Section 3 studies types of the ERS for boom energy. And ERS for swing energy is presented in Section 4. Section 5 presents the challenges, market opportunities and future developments of ERS. Conclusions are compiled in Section 6.

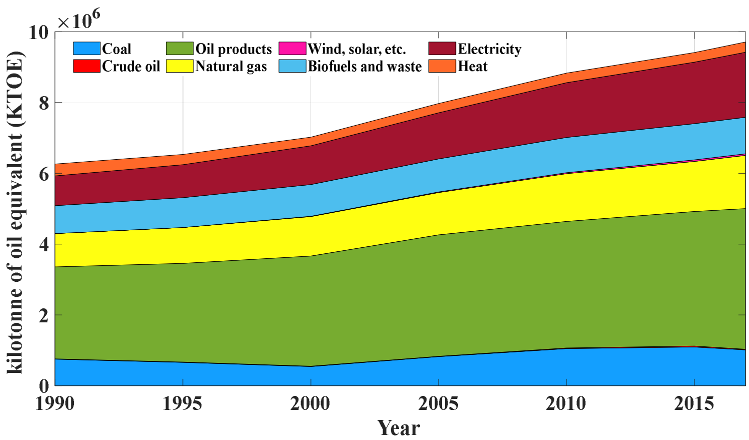


Figure 1. Total final consumption (TFC) by source, World 1990-2017 (Source: IEA World Energy Statistic and Balances https://www.iea.org/data-and-statistics. [1]).

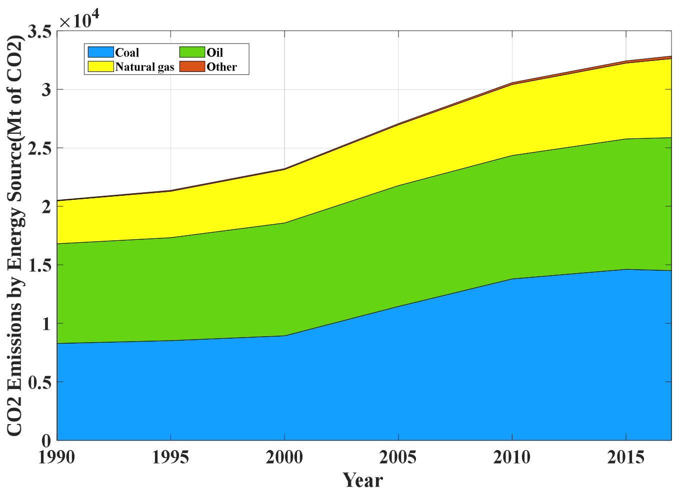


Figure 2. CO_2 emissions by energy source, World 1990-2017 (Source: IEA World Energy Statistic and Balances https://www.iea.org/data-and-statistics. [9])

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 [17-20]. 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 [13, 21], the pressure and flow rate of each part in a 20-t HE are experienced as shown in table 1. The potential energy that the boom cylinder can be generated is 51% and in 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. 3 and Fig. 4. Hence, a lot of methods and structures have been proposed to maximize these energies according to different working conditions. Typically, they will be converted into different forms of energy depending on the energy storage device of the ERS.

Table 1. Potential energies in HE. [21] Copyright 2017. Elsevier

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

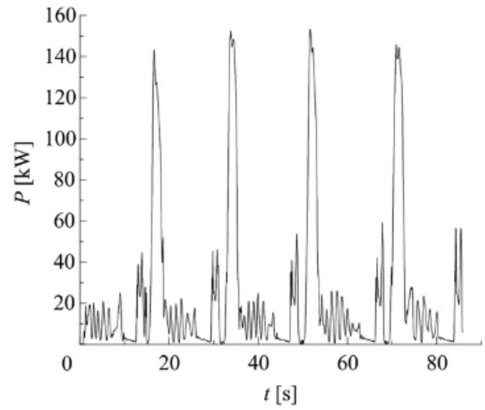


Figure 3. Power requirement of HE in digging condition. [13] Copyright 2010. Elsevier

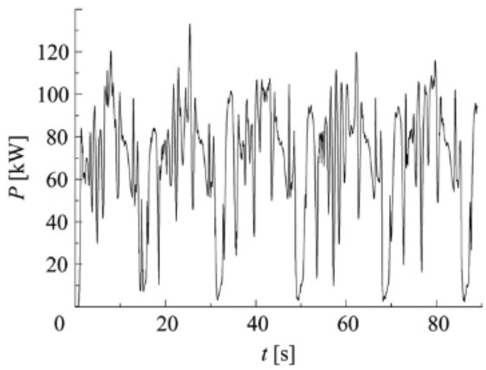


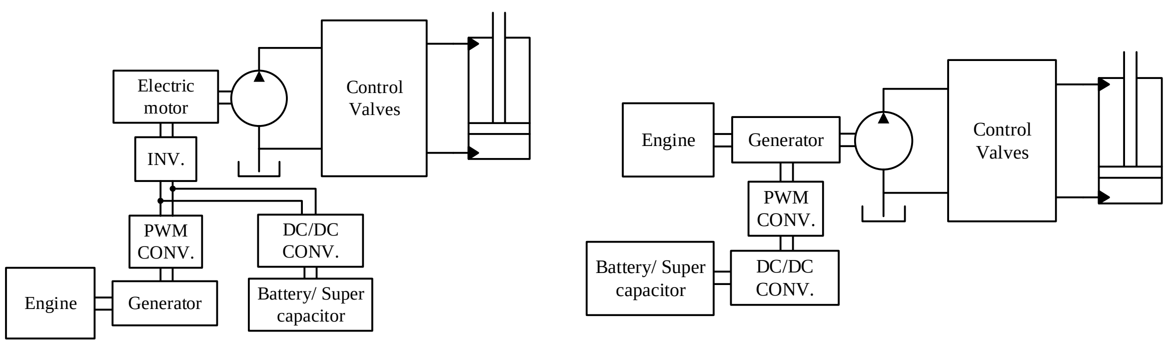
Figure 4. Recoverable energy of the boom cylinder in digging condition. [13] Copyright 2010. Elsevier

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

The structure of 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 as shown in Table 1. 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.

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) by 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 [22-24]. 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 [25]. In 2008, Komatsu [26] released a full-scale HHE PC200-8 using the combination of an electric motor and the ICE in the compound category. Kwon et al. [27] 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. 5. 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” [27]. 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.



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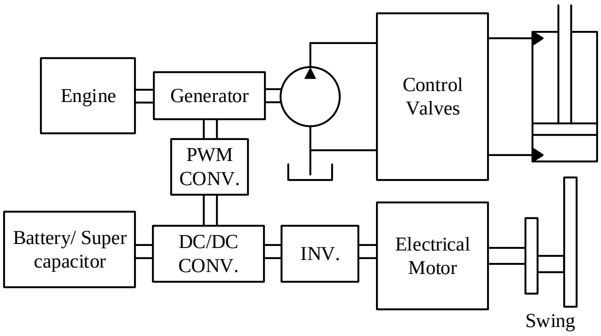

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Figure 5. Different structures of HE. (a) Series type. (b) Parallel type. (c) Compound type. [27] Copyright 2010. IEEE

Among three different structures of hybrid power sources, Xiao et al. [28] focused on studying the parallel hybrid type which had the lowest additional cost [27]. 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. 6).-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.

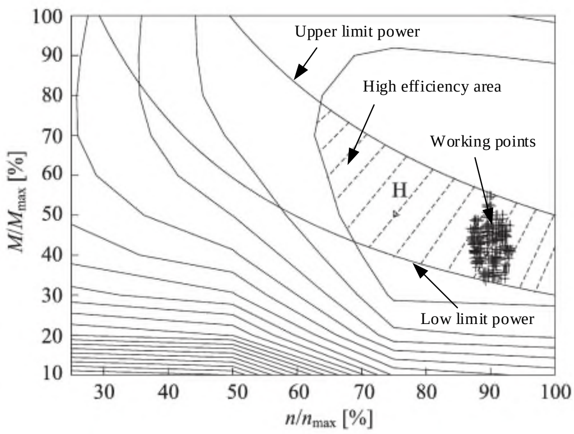


Figure 6. Distribution of engine working points with the hybrid system. [28] Copyright 2008. Elsevier.

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. 7. 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.

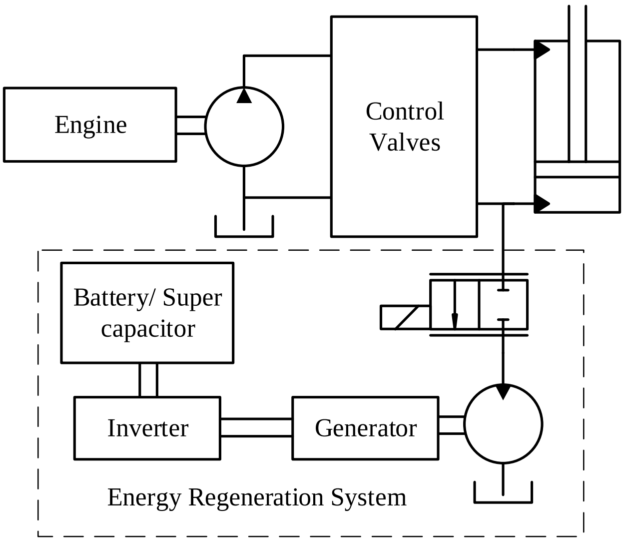


Figure 7. A classical ERS using electrical storage.

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. [29] proposed a control strategy to enhance the boom performance whilst underpinning the high energy recoverability as shown in Fig. 8. Here, characteristics of the classical ERS were modeled 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. [15] 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.

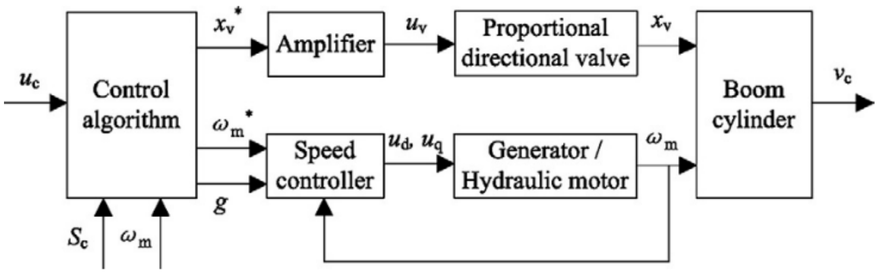


Figure 8. Structure of the energy recovery controller. [29] Copyright 2013. Elsevier.

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. [30, 31] proposed a hydraulic boom system using EHA as shown in Fig. 9. 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. [32] proposed a new configuration of boom system in which EHA was used as the primary power supply. Knussman et al. [33] 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. [34] 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 [35, 36]. Therefore, EHAs are generally unsuitable for large size HEs.

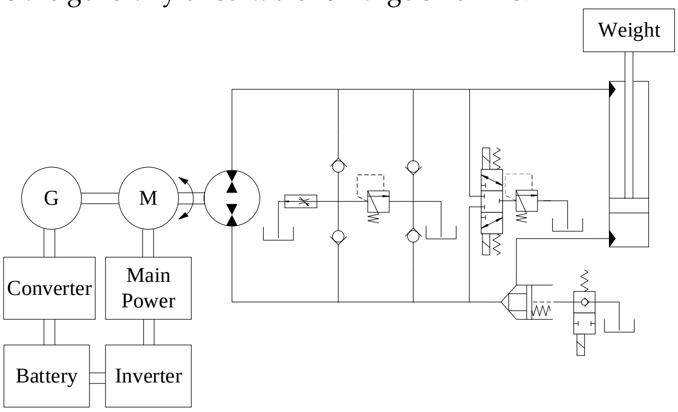


Figure 9. The electric HE using EHA.

Ge et al. [37] replaced the conventional ICE of HE by using a servo-electric motor driving a variable displacement pump as the main power source. 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 shown in Fig. 10 and Fig. 11. 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).

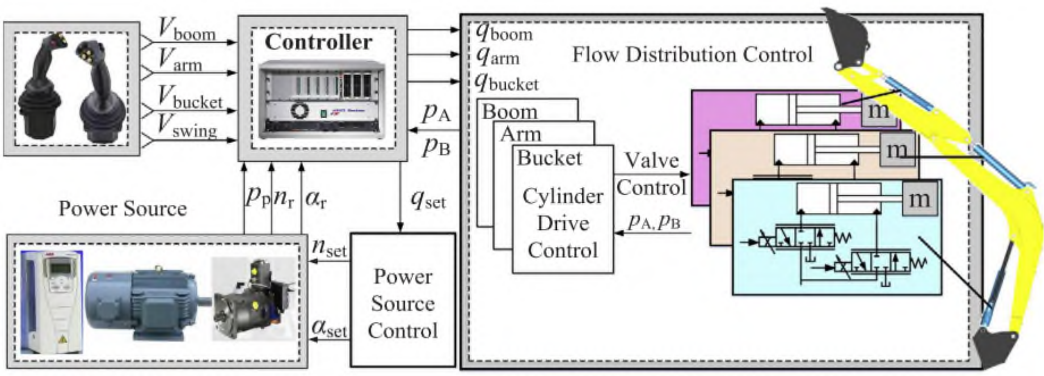


Figure 10. Structure of electric HE using the variable pump and the servo motor. [37] Copyright 2017. Elsevier.

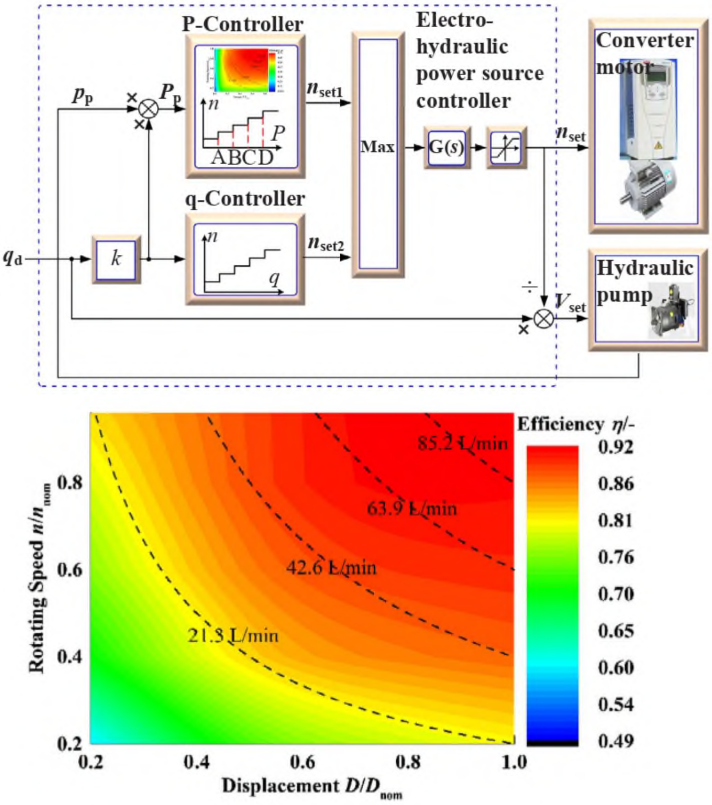


Figure 11. Power source control strategy and efficiency map of the pump. [37] Copyright 2017. Elsevier.

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. [38] 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. 12. 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%.

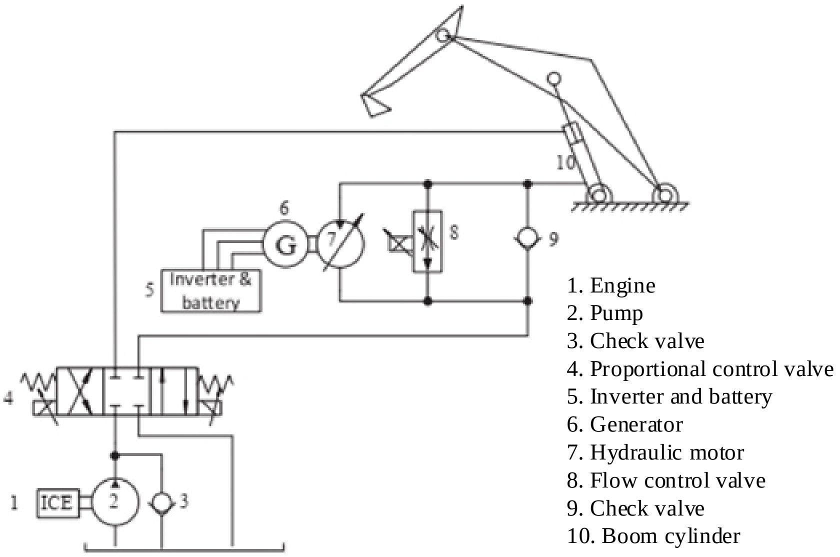


Figure 12. ERS of boom system using an additional flow control valve. [38] Copyright 2019. Elsevier.

To solve the low-efficiency problem and reduce the size of energy recovery devices in conventional ERS, some authors [39-41] proposed a novel electric ERS structure that integrated an additional hydraulic accumulator as shown in Fig. 13. 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. 14. "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" [40].

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. 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 [15, 37-39]. 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 [25, 27, 28, 30, 41].

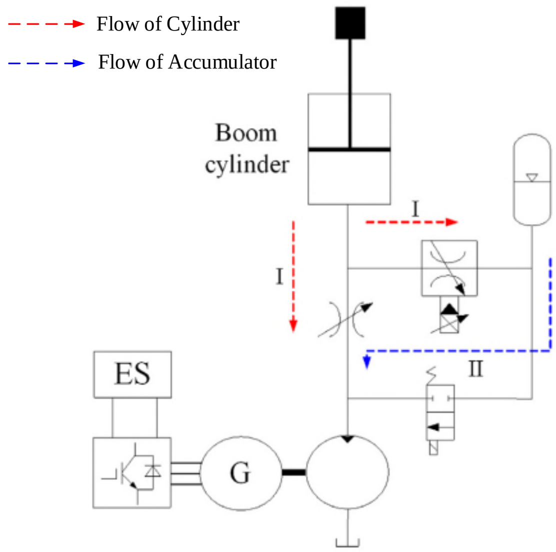


Figure 13. ERS of boom system with additional hydraulic accumulator. [39] Copyright 2019. Elsevier.

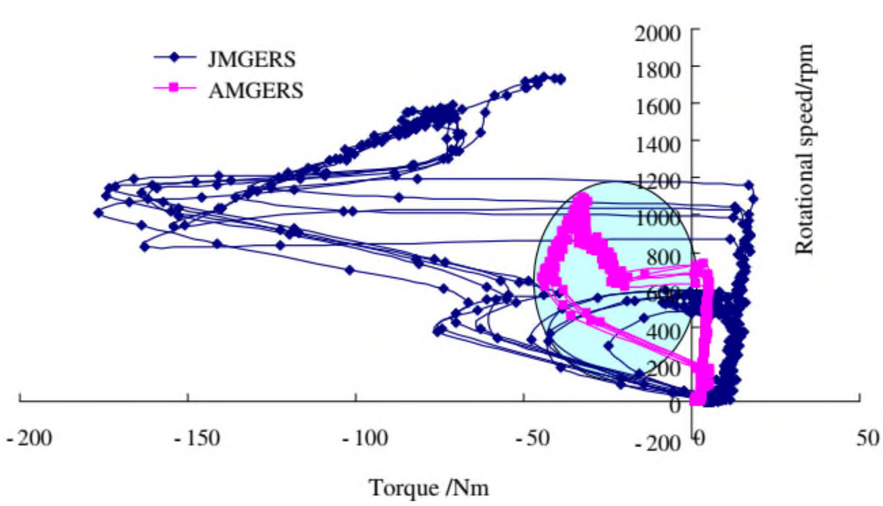


Figure 14. Distribution of the working points of the generator with the hydraulic accumulator (AMGERS) and without hydraulic accumulator (JMGERS). [40] Copyright 2019. Elsevier.

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

Ref.	Novelty	Energy Regeneration Efficiency	Power Consumption Reduction	Merits	Demerits
[25]	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
[28]	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.
[30]	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.
[27]	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.

[41]	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.
[15]	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
[31]	A control strategy for motor speed based on the real system [30]	-	47.8%	- Significantly reduces energy consumption.	- Low regenerated energy. - The system has not been verified with the load condition
[29]	A control strategy with load torque observation and flow compensation to enhance the performance of ERSs	64.5%	-	- Improved the dynamic performance. - High energy regeneration efficiency.	- Required large sizes generator and hydraulic motor.
[40]	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.
[37]	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
[39]	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
[38]	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.

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. 15 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.

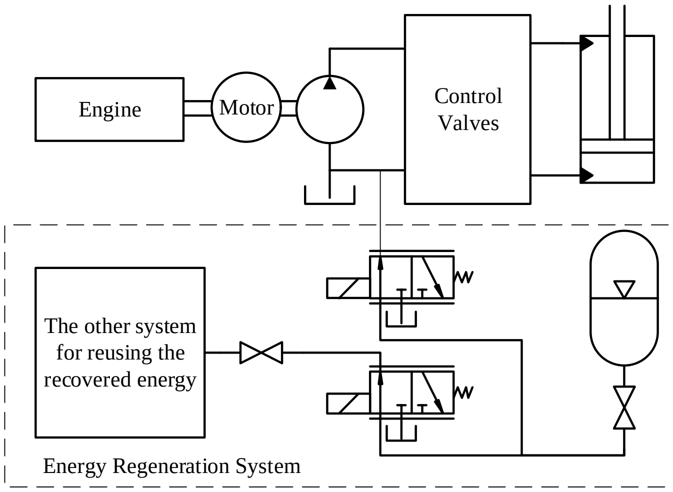


Figure 15. Schematic of the ERS using hydraulic storage.

Bui et al. [32] suggested a new configuration for HE using EHA, an accumulator and two hydraulic transformers as shown in Fig. 16. 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. [33] 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. [42] 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 [32], Zimmerman et al. [43] 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.

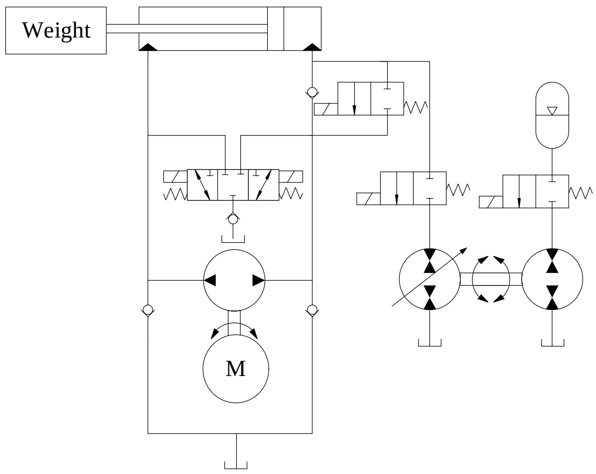


Figure 16. Schematic of the potential energy recovery system of the HHE using the electro-hydraulic actuator (EHA). [32] Copyright 2015. IEEE.

Shen et al. [44] 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 17. 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. 18.

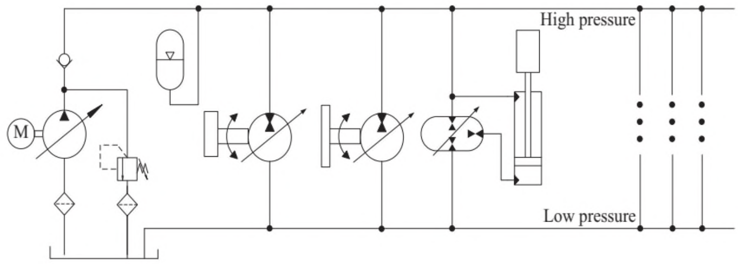


Figure 17. Structure of the Common Pressure Rail system. [44] Copyright 2015. Elsevier.

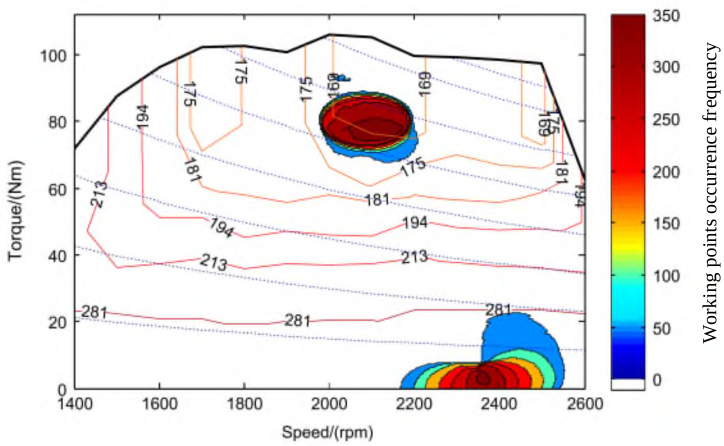


Figure 18. Working points occurrence frequency map under adjustable single point strategy. [44] Copyright 2015. Elsevier.

Ge et al. [45, 46] proposed a ERS scheme with a hydraulic accumulator and an energy conversion cylinder as presented in Fig. 19. 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. 20. 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.

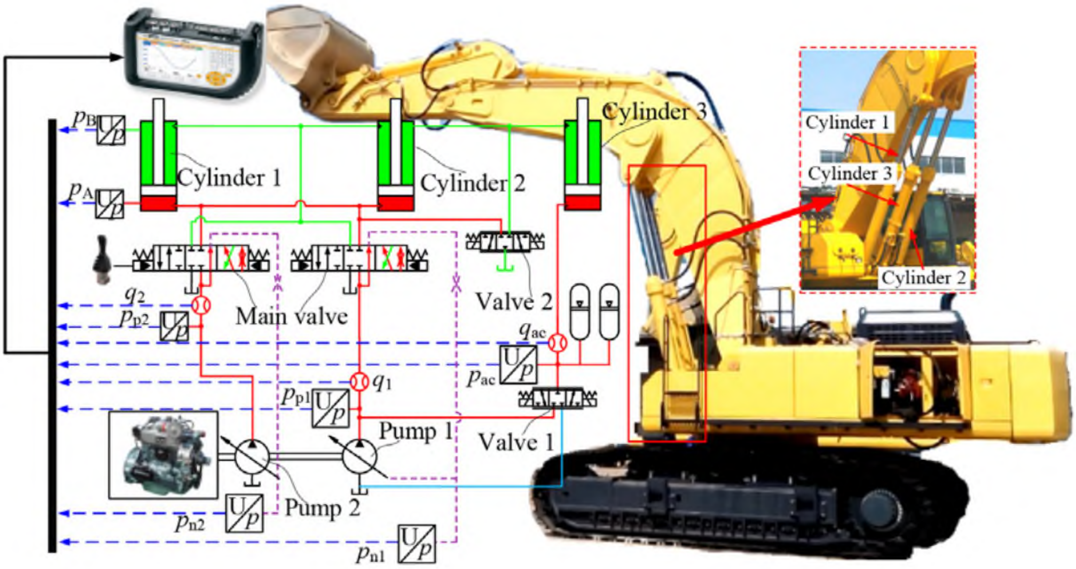


Figure 19. Working principle of the balance boom cylinder system. [45] Copyright 2019. Elsevier.

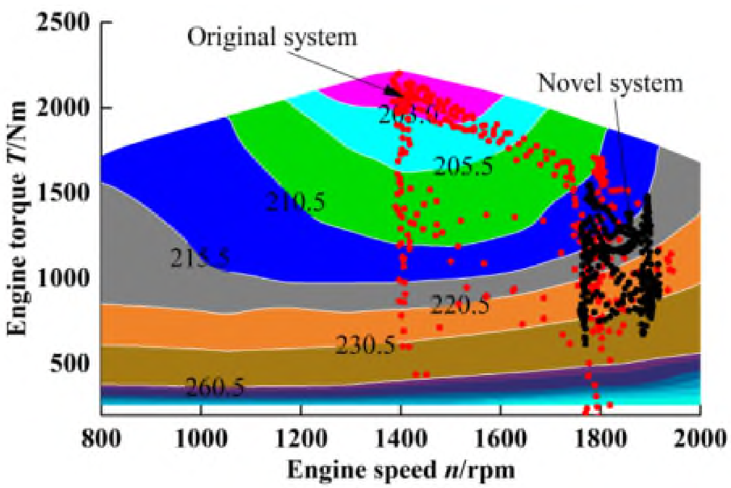


Figure 20. Operating points over five excavation cycles. [45] Copyright 2019. Elsevier.

Chen et al. [47] 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. 21. 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.

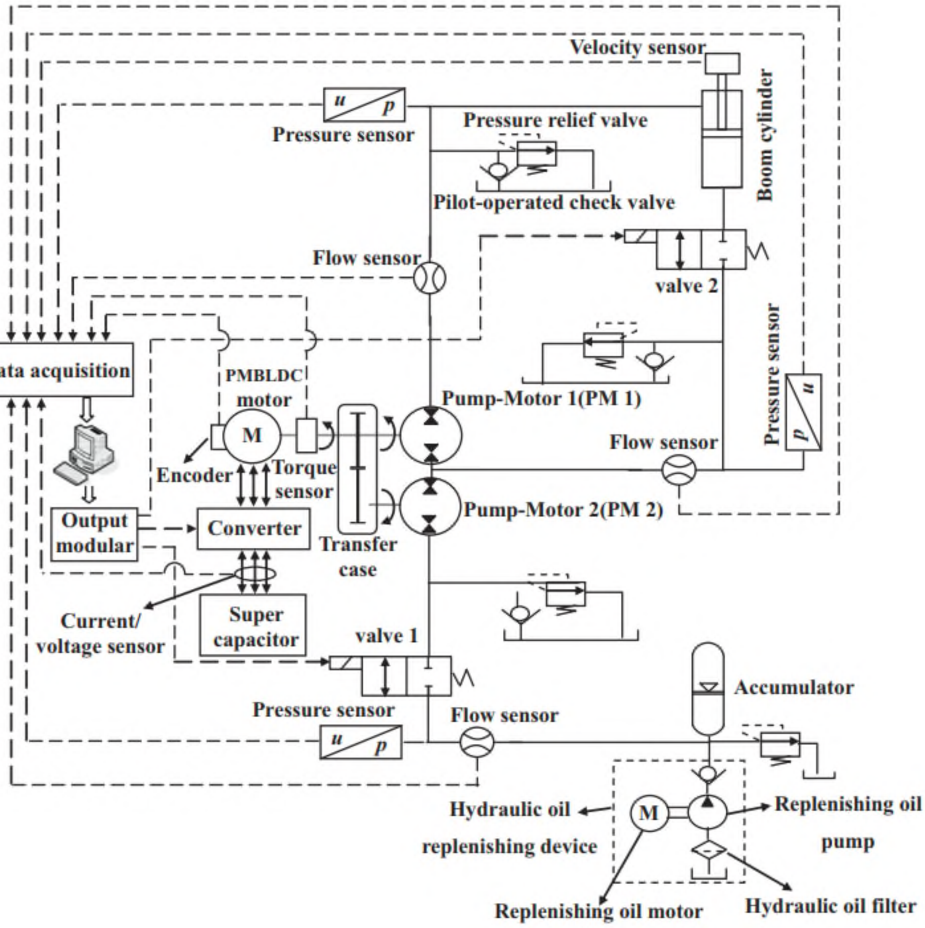


Figure 21. Schematic diagram of the closed-circuit gravitational potential energy regeneration system (GPERS) of the boom. [47] Copyright 2017. Elsevier.

Xia et al. [48] proposed a new configuration of ERS using three-chamber hydraulic cylinder as shown in Fig. 22. 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. 23. 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.

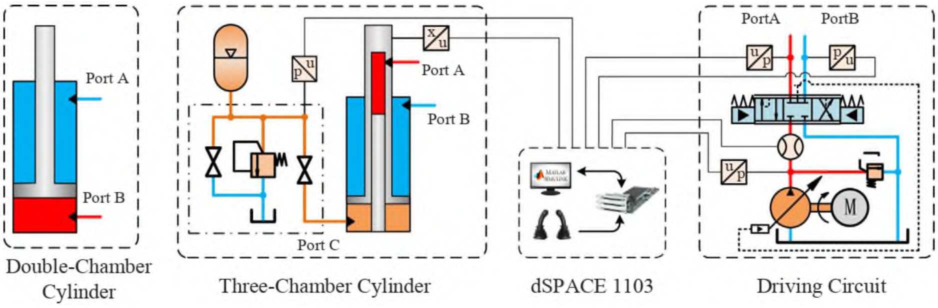


Figure 22. Test schematic of the double and three-chamber cylinder systems. [48] Copyright 2018. Elsevier.

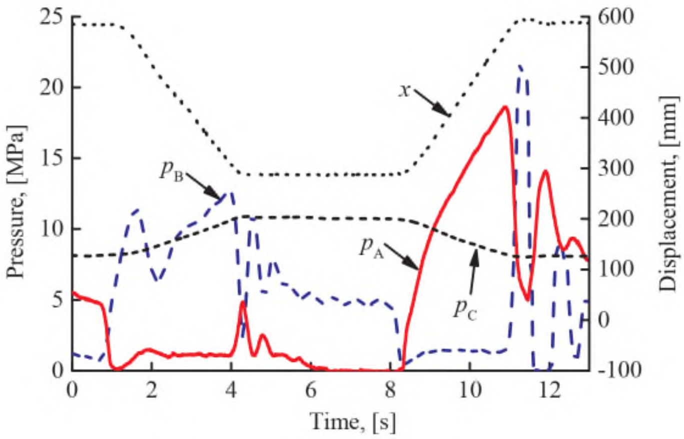


Figure 23. Pressures and displacement of three chambers cylinder. [48] Copyright 2018. Elsevier.

Ge et al. [35] proposed a novel-designed asymmetric pump to decrease the energy consumption of a HE boom system as shown in Fig. 24. 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. 25. 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 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.

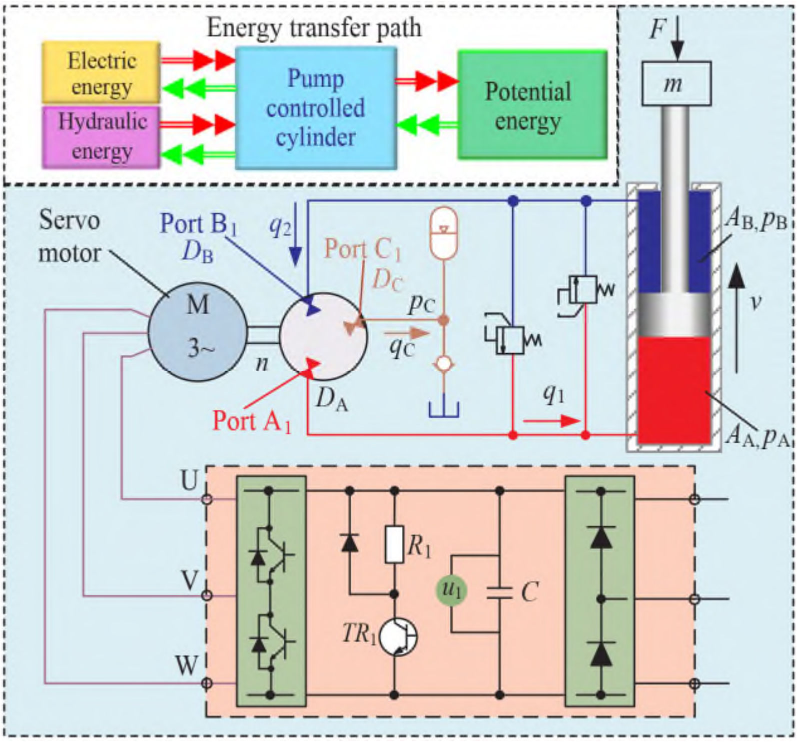


Figure 24. Principle and structure of the novel-designed asymmetric pump system. [35] Copyright 2018. Elsevier.

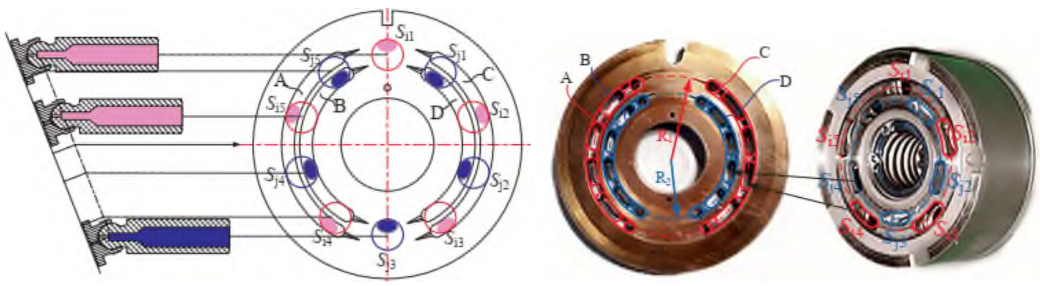


Figure 25. Working principle and the image of the valve plate and cylinder block. [35] Copyright 2018. Elsevier.

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

Ref.	Novelty	Energy Regeneration Efficiency	Power Consumption Reduction	Merits	Demerits
[49]	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
[50]	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.
[51]	A digital flow control unit consists of two individually adjustable control edges containing five poppet-type on/off valves for flows division.	45%	-	- Directly recovery and store the energy in accumulators.	- Not suitable with variable load conditions. - Occupied a lot of installation area
[32]	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.

[44]	Secondary components (pump/motor and Hydraulic Transformer)	-	↓38.2%	- Reduced power consumption	- Not consider the energy regeneration efficiency. - Too expensive.
[52]	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
[53]	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
[47]	ERS using a closed-circuit hydrostatic transmission	60% - 68.2%	-	- High energy regeneration efficiency. - Good control performance.	- High cost. - Complicated system structure.
[54]	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.
[48]	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
[35]	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.
[55]	ERS using a hydro-pneumatic accumulator, a hydro-motor, and a loading pump.	-	↓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
[45]	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
[46]	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

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. [56] proposed a new mechanical ERS integrating a flywheel, a variable hydraulic pump/motor and a regeneration flow control valve as shown in Fig. 26. 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.

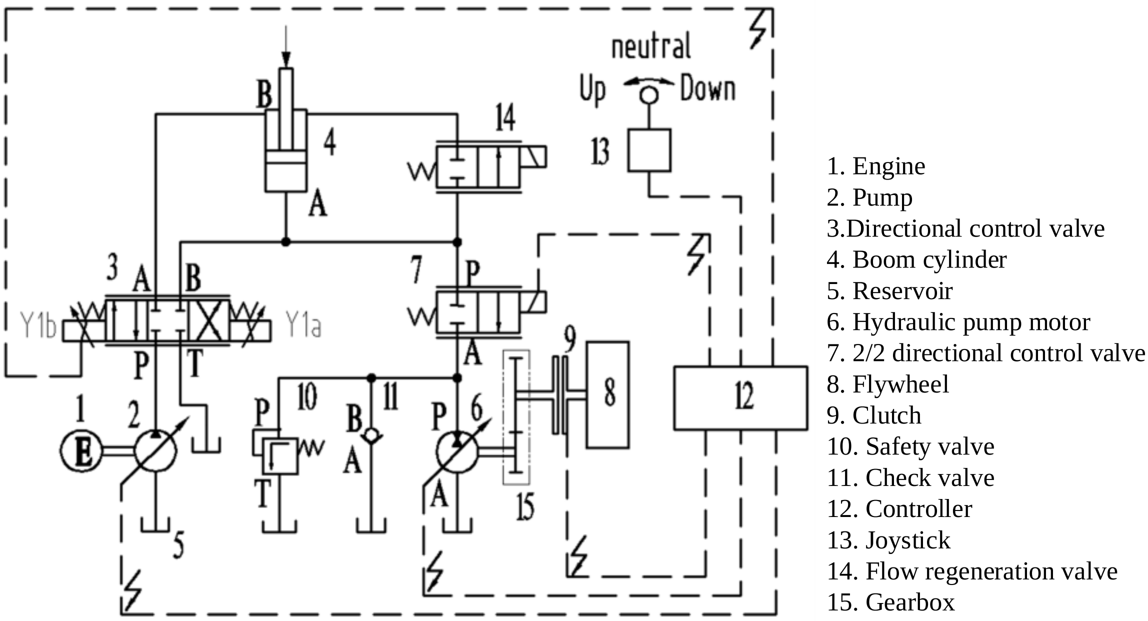


Figure 26. Structure of a flywheel mechanical ERS. [56] Copyright 2020. MDPI.

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 as shown in Table 4. 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 according to Table 1. 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. [57] 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. 27. 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.

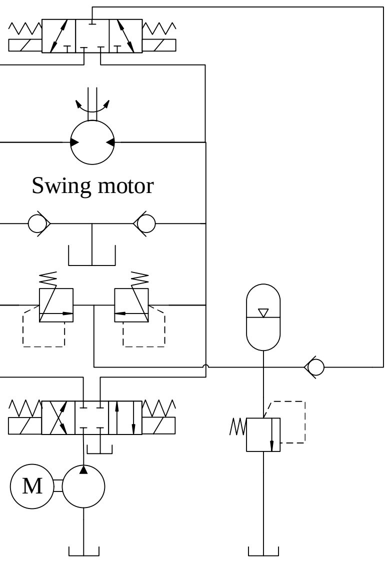


Figure 27. Schematic of hydraulic ERS swing system. [57] Copyright 2015. IEEE.

Chowdhury et al. [34] replaced the conventional hydraulic circuit by using an EHA system as shown in Fig. 28. 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.

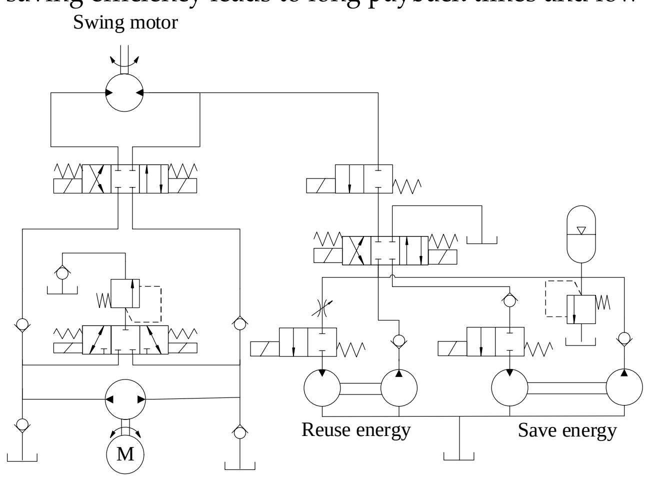


Figure 28. The ERSs of the swing system using two pair of hydraulic pump and motor. [34] Copyright 2015. IEEE.

Xiao et al. [58] proposed a new hydraulic system for the swing system with a hydraulic accumulator and two flow control valve as shown in Fig. 29. This system had some similarities with the presented system in a previous patent [59]. 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 V_1 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%.

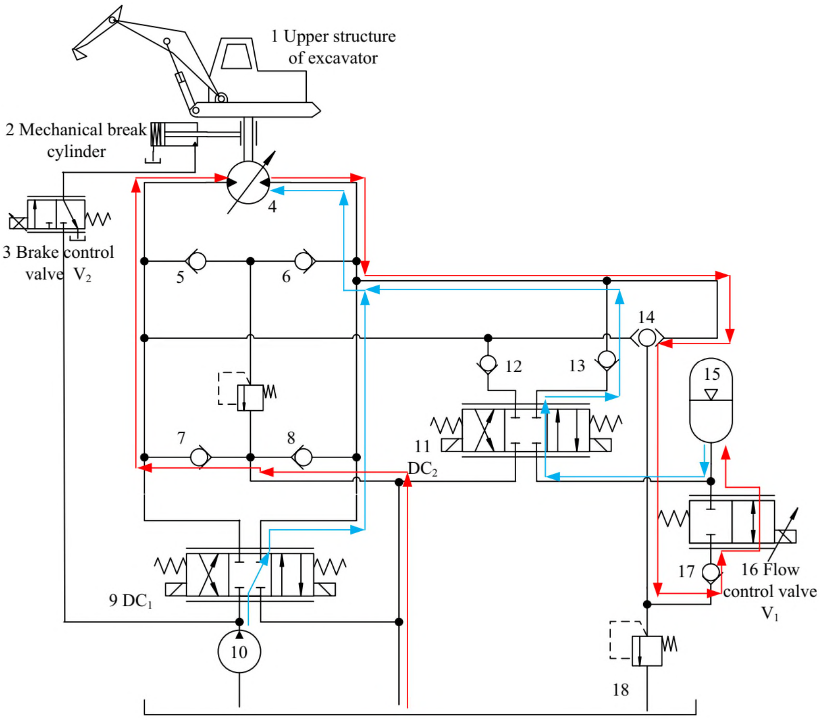


Figure 29. Hydraulic circuit of the ERS system using an accumulator and a flow control valve. [58] Copyright 2019. Springer.

Based on the above research [58], Xiao et al. [60] 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. 30. 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. [61] 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.

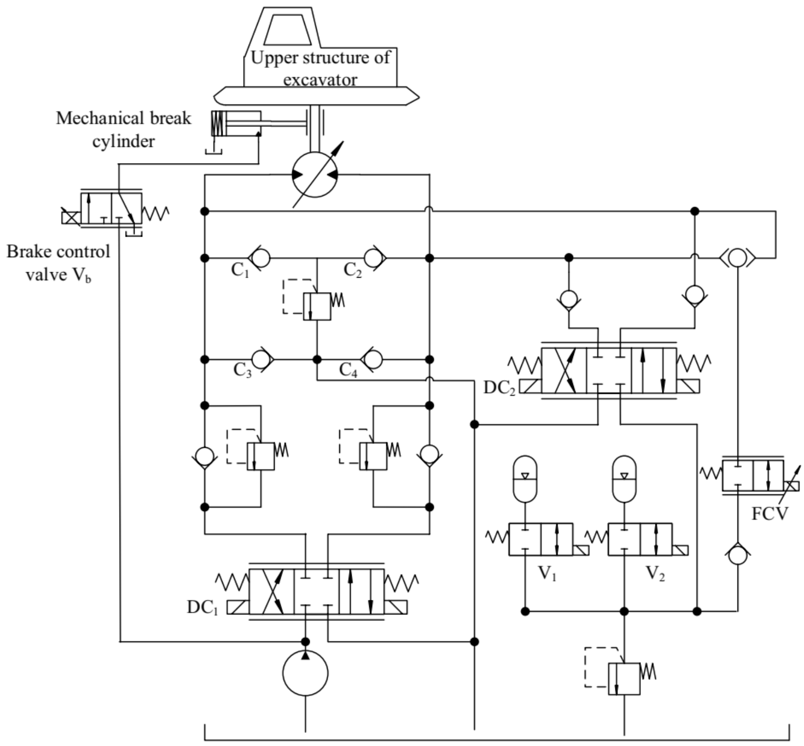


Figure 30. Hydraulic circuit of the ERS system using two independence accumulators. [60] Copyright 2019. Springer.

During the acceleration process, Zheng et al. [62] 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. [63] 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. [64] 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. [65] 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. 31. 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. [66] 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 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.

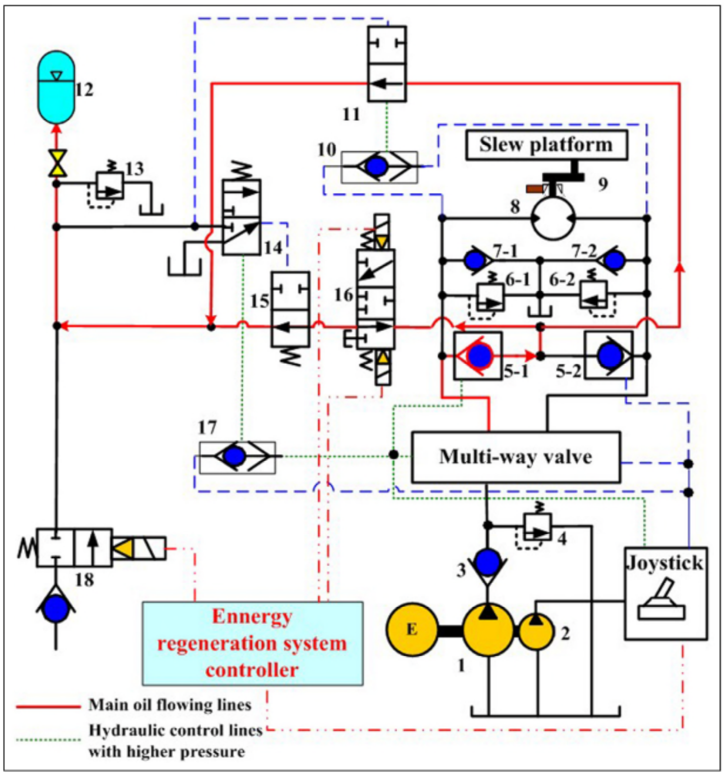


Figure 31. Proposed ERS system using accumulator for swing acceleration process. [65]

Table 4. Technology summary table of swing ERS.

Ref.	Novelty	Energy Regeneration Efficiency	Power Consumption Reduction	Merits	Demerits
[57]	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.
[34]	ERS using two pairs of the hydraulic pump and motor	22.75%	-		- The structure was cumbersome and ineffective - Long expected payback periods
[58]	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.
[60]	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.
[62]	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.
[65]	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
[66]	ERS using hydraulic motor and generator		38%	- Can regenerate the energy in both acceleration and deceleration processes.	- High energy loss.

5. Challenges, market opportunities and future development of hydraulic excavator

5.1. Challenges

Based on the above analysis, it can be seen that 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 [21] 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.

5.2. Market opportinuties

A number of energy recuperation technologies have been deployed within the construction equipment industry. The world first hybrid excavator PC200-8 (20-ton class) manufactured by Komatsu in 2008 is one example [26]. This machine employes an electric motor for its swing actuator, an integrated ERS which comprised a dynamo motor, an inverter, a capacitor and other components to capture kinetic energy during the swing deceleration. The energy is stored as electricity in the capacitor and can be reused to assist the engine during the acceleration. Compared to the conventional version of PC200-8, the hybrid model could save up to 25% of fuel consumption. Under high frequencies of the swing operation, a fuel reduction up to 41% could be achieved. In 2010, a full model using the developed components (generator/motor, swing electric motor/generator, inverter and capacitor) by Komatsu is upgraded to HB205/HB215LC-1. Later in 2013, Komatsu developed 30-ton class hybrid hydraulic excavator HB335/HB365-1 model [67]. The swing brake regeneration energy technology is still implemented in these models. In order to improve efficiencies of the transmission and the power generation mechanism as well as the fuel reduction capacity, Komatsu changed the dynamo motor in the previous versions to a motor-generator which was built between the engine and the hydraulic pump. An average of 20% of additional fuel saving is achieved in the HB335/HB365-1 model compared to the standard PC300-8 model. And in 2016, an upgraded version HB335-3/HB365-3 was developed to further improve fuel consumption and quietness [68]. Thanks to the control method of engine speed and fan clutch, the fuel consumption is cut by 22% compared to the standard version PC300-10 and the noise level is remarkably reduced. The engine is controlled as regards the load to reduce the rotation speed. Moreover, a fan clutch is installed and operated at optimum speeds with respect to the engine coolant and hydraulic oil temperatures.

If Komatsu has focused mainly on kinetic energy recovery through swing actuators, Bosch Rexroth has paid more attention to saving excess energy of the traditional hydraulic system and kinetic energy of the ICE in HEs through ERS using hydraulic flywheel (HFW) [69]. The ERS is coupled with the ICE and consists of a variable axial piston pump, a high pressure hydraulic accumulator, a valve control block with a pressure regulator and an electronics BODAS controller. The system is able to store the excess energy as well as the kinetic energy when the engine is only partly loaded and then reuse it if necessary. The developed technology then offers several benefits, including downsizing capability, fuel saving, and overspeed protection.

At Kobelco and Volvo, energy recuperation from both boom and swing actuators in HEs are of their interest. For instance, in 2006, a 6-ton class hybrid excavator was developed through a collaborative effort between Kobelco Construction Machinery, Kobe Steel, and NEDO [70]. The boom is driven by an EHA-based system consisting of an electric motor and a bi-directional hydraulic pump. Potential energy which is accumulated during boom up process is then regenerated as electric energy via the hydraulic pump during the boom down process. The results show that the reduction in fuel consumption can reach up to 40-60%, compared to the conventional excavators. In 2012, an 8-ton class hybrid hydraulic excavator SK08H was developed by Kobelco to harvest energy through its swing operation [71]. The model has reduced 40% of the fuel consumption and deceased the noise level compared to the 2006 model. Meanwhile, Volvo introduced their newest hybrid excavators EC300E HYBRID in 2020. Here, the excavator utilizes the boom down motion to charge an accumulator. The stored energy is then re-used to drive hydraulic assist motors which help accelerate the engine system. By deploying this technology, up to 20% of fuel economy could be improved compare to the conventional EC300E excavator [72].

Table 5 then summarizes the current commercialization and future commercial opportunities of energy regeneration technologies.

Table 5. Market opportunities for proposed ERSs.

Technology	Cost Impact	Comments/ Commercial Potential	Commercial Product
Boom ERS using accumulator [49-51, 53, 54]	Lower lifecycle cost due to durable hydraulic components. Expensive with auxiliary components such as variable hydraulic motor or transformer Short payback time due to high energy regeneration efficiency	- easily integrated into HEs - not suitable for small size excavators since large installation space is required - suitable for those needed to start/stop frequently	- Bosch [69] - Volvo EC300E HYBRID [72]
Boom ERS using battery/ supercapacitor [15, 25, 28, 29, 38]	High investment cost due to extra hydraulic motor, electric motor and batteries Long pay-back time due to medium energy regeneration efficiency	- more suitable for electric HEs since it already has battery/supercapacitor storage devices - the electric actuators can be driven directly by the regenerated energy	- Kobelco 6 ton-class and 8 ton-class SK08H [70, 71] - Hitachi ZAXIS 200 [73]

	High lifecycle cost due to electric components.		
Boom ERS using mechanical flywheel [56]	High investment cost due to extra hydraulic motor/pump and flywheel Long pay-back time due to energy loss Low lifecycle cost due to due to durable mechanical components.	- Suitable for small HEs due to the size of flywheel.	
Boom ERS using combination of accumulator and battery/capacitor [39-41]	High investment cost due to extra hydraulic motor, electric generator, battery and accumulator. Long pay-back time due to medium energy regeneration efficiency. High lifecycle cost due to complex structure.	- more suitable for an electric hybrid HE since it already has battery/supercapacitor storage devices,	
Boom ERS using balance cylinder or three chambers cylinder. [45, 46, 48]	Low investment cost due to using a hydraulic accumulator and an additional cylinder. Short pay-back time due to high energy regeneration efficiency. Low lifecycle cost due to high durable components	- Suitable for all kind of excavators	
Boom ERS using a novel asymmetric pump [35]	High investment cost due to asymmetric pump and accumulator. Short pay-back time due to high energy regeneration and saving efficiencies. High lifecycle cost due to directly controlling the cylinder by pump.	- Suitable for small and medium size of excavators due to controlling the boom cylinder without valves.	
Swing ERS using accumulator [32, 35, 44, 45, 47-55]	Expensive with auxiliary components such as variable hydraulic motor or transformer Long pay-back time due to low energy regeneration and saving efficiencies. High lifecycle cost due to variable hydraulic transformer.	- Simple structure and suitable for all kind of excavators with systems using accumulators and valves. - Complex structure and not suitable for commercial HEs using accumulator and variable hydraulic transformers.	
Swing ERS using electric motor and capacitor and/or battery [66]	High investment cost due to additional devices. Short pay-back time due to high power saving efficiency High lifecycle cost due to electric components.	- This configuration is chosen by a large number of manufacturers - more suitable for electric hybrid excavators since it already has battery/supercapacitor storage devices	- Komatsu PC 200-8 hybrid [26] HB205/HB215LC-1 HB335/HB365-1 [67] HB335-3/HB365-3 [68] - Kobelco 6 ton-class and 8 ton-class SK08H [70, 71] - Hitachi ZAXIS 200 [73]

5.3. Future development

5.3.1. Development directions

Due to the complexity and cost of ERSs, one potential route is to develop an ERS which capable of working with more than one actuator in HEs. For example, Ranjan [55] proposed the ERS using a hydraulic accumulator that could recovery both potential and kinetic energy generated from the boom and swing systems, respectively. As shown in Fig. 32, when the swing accelerates, the directional control valve (DCV) 23 and 25 are opened to charge the power from the main pump to the accumulator. Here, the accumulator works as a surge component to reduce excessive pressure during the start of the electric motor. During moving down of the boom cylinder, the DCV 16 works at the right position, and the flow rate from the bore chamber is charged into the accumulator via DCV 28 which works in the right position. In subsequent cycles, the energy stored in the accumulator could be reused to supply the boom systems through the DCV 28 and DCV 27. The experiment results showed that this proposed architecture could enable a fuel saving by 10% compared to the conventional HE without ERS.

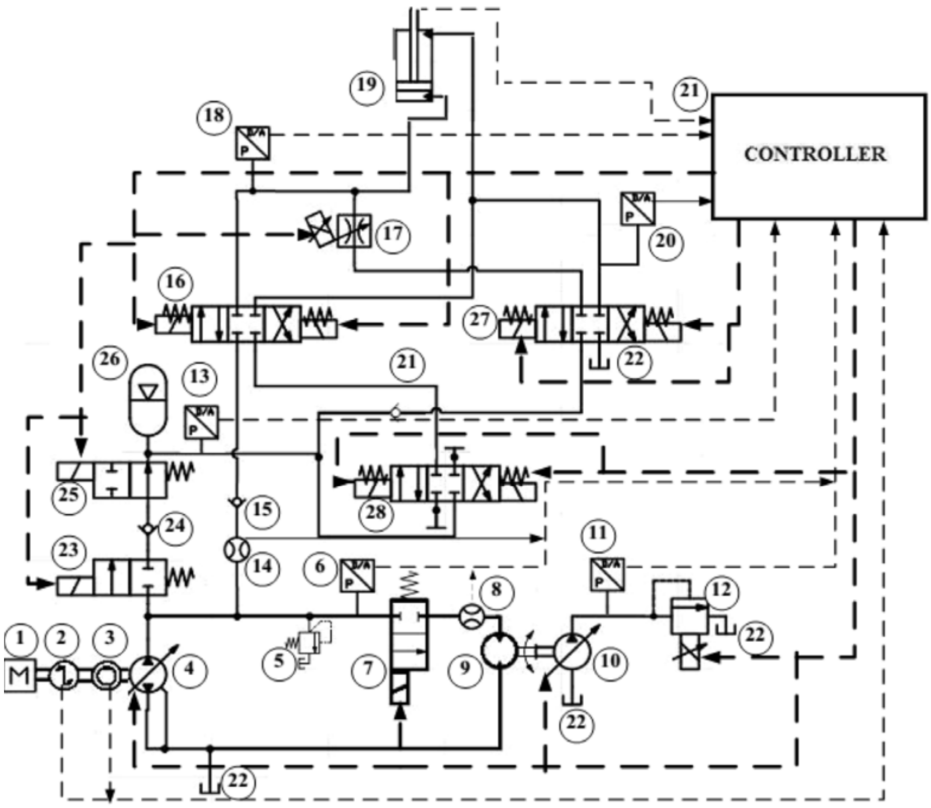


Figure 32. Hydraulic circuit of the ERS system for the boom and swing systems. [55] Copyright 2020. Elsevier. 1, motor; 2, 3, sensor; 4, 10, pump; 5, 12, relief valve; 6, 11, 13, 18, 20, pressure sensor; 7, 16, 23, 25, 27, 28, control valves; 8, 14, flow sensor; 9, hydraulic motor; 15, 24, check valve; 17, flow control valve; 19, cylinder; 21, controller; 22, control signal; 26, accumulator.

The current state-of-art reviewed above indicates that ERSs are acknowledged for its rapid growth. In the electrical ERSs, most of the energy loss due to transformation of energy (hydraulic-mechanical-electrical) through a pair of hydraulic motor and generator in which their efficiencies are unstable and influenced by the system flow rate and pressure. Therefore, a potential solution is to develop a new energy conversion device which can directly and effectively convert between the electrical and hydraulic energy. For instance, Liangliang W. et al. [74] introduced a low-speed and high-efficiency permanent magnet generator (LHPM generator) consisting of a hydro kinetic energy turbine and three-phase direct-drive permanent magnet generator. Here, water from renewable energy sources was passed through a channel to interact with blades of the turbine and convert the water energy into rotational energy. Then, LHPM generator was rotated and generated the electrical power without any gearbox as shown in Fig. 33. The efficiency of LHPM generator could reach up to 86.4% at low speed. The same working principle could be utilized for the development of high-efficiency electrical ERSs.

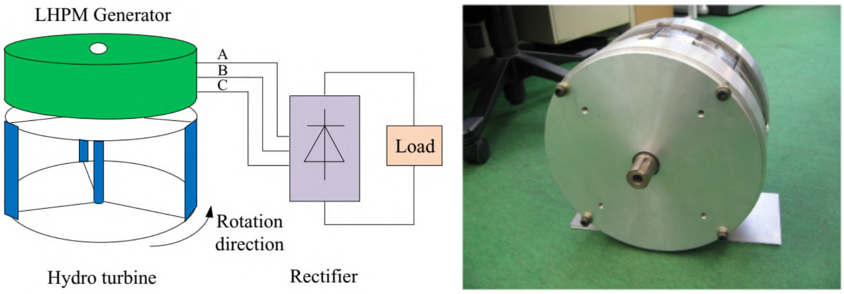
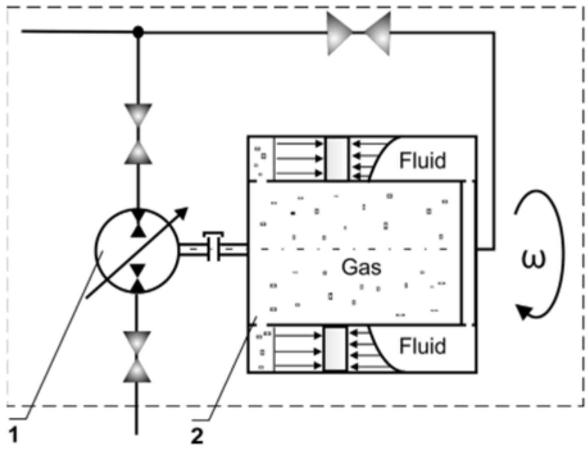


Figure 33. Hydraulic circuit of the ERS system for the boom and swing systems. [74] Copyright 2020. Elsevier.

In hydraulic and mechanical ERSs, accumulators and flywheels are the key components. Although accumulators offer a lot of advantages (such as directly store and discharge energy in form of pressurized fluid, emergency backup, vibration and shock reduction), a major drawback is that pressure changes in accumulator directly impact the system performance. High and low initial pressures could hinder the cylinder movement and increase energy loss, respectively. Meanwhile, mechanical flywheels can quickly store the kinetic energy. However, the problem of the flywheel is that the recovery energy is related to the rotation speed of the flywheel and decreases with time due to friction in the mechanical parts. Therefore, to develop ERSs using mechanical and hydraulic storages, a new generation of these devices taking their all advantages is necessary. For example, Waldemar L. et al. [75] presented a new type of hydrokinetic accumulator which comprises two key elements, a flywheel of variable moment of inertia (due to inflow or outflow of hydraulic fluid) and a variable displacement pump/motor. During the recovery process, both potential and kinetic energies of boom cylinder or swing motor are stored in the hydrokinetic accumulator (pressurized fluid and rotational speed) via the variable displacement pump/motor as shown in Fig 34. Hence, the hydrokinetic accumulator is not only a significant increase in energy density but also decoupling the state of charge from the pressure in the hydraulic system by reusing one of the stored energies.

Until now, researchers are focusing on recovering as much energy from the HE as possible. Meanwhile research and development on how to maximise efficiency in reusing the recuperated energies, especially in electrical ERSs, are also of significant importance and thus, require further intention. Developing simple and affordable ERSs to effectively tackle both the energy generation and re-using challenges should be conducted in the near future.

Besides improving energy recovery efficiency, reducing associated costs is also an important factor to accelerate the commercialization of energy regeneration technologies in HEs as well as to improve the customer acceptance. Machine cost saving could be achieved by developing a next generation of energy conversion and storage devices at cheaper costs. For instance, cost of Li-on batteries is projected to be decreased by approximately 11% annually from 2007 to 2017 (1000 US dollar/kWh compared 140 US dollar/kWh) [76, 77]. Meanwhile, operation cost saving could be achieved by the use of energy management strategies to optimise the machines' key indicators, such as fuel consumption, efficiency, and component lifetime. For example, Xiaosong H. et al. [78] proposed a cost-optimal energy management for hybrid electric vehicle. Here, the total running expense of a fuel cell/battery hybrid electric vehicle, calculated based on hydrogen, fuel cell and battery degradation costs, is minimized using the advanced health-aware model predictive control. The results show that the operation cost could be saved up to 36.4%. This management technique is clearly applicable to HEs to maximise performance of ERSs.



1. Variable displacement pump/motor
2. Flywheel of variable moment of inertia

Figure 34. Hydraulic circuit of the ERS system for the boom and swing systems. [75] Copyright 2018. Elsevier.

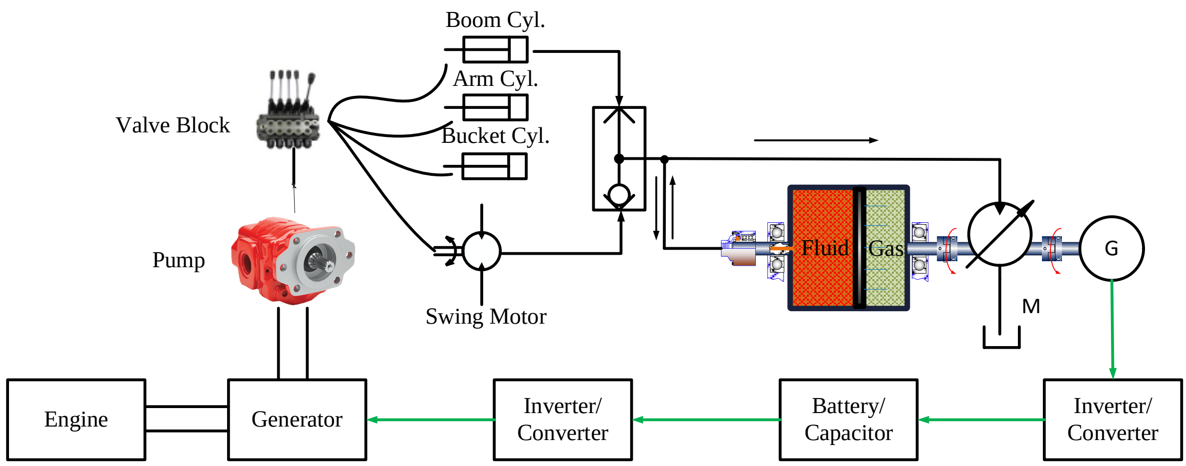


Figure 35. The combined regeneration hydraulic lines with HFA, hydraulic motor and generator

5.3.2 A proposed solution

The regeneration system always requires at least one energy storage device. However, using a single storage device is difficult to meet the need for energy recuperation as well as performance satisfaction of excavators. Some researches combine two independent energy storage devices to form a combined energy storage system. For instance, battery and supercapacitor are normally used together to utilise their advantages of both energy density (battery) and power density (supercapacitor) [79, 80]. Another way to improve the energy saving potential is acknowledged as the combination between other kinds of energy storages. And hydraulic-flywheel-accumulator (HFA) is one of the most feasible solutions. The HFA concept was first proposed by Van d. V. [81], leading to further studies on HFAs for different applications. For example, Dung applied this design concept in a combined wind, wave and tidal energy converter system [82]. The simulation results show that, compared to a traditional hydraulic accumulator with the same volume, the energy capacity of the HFA could be 10 times greater (1209 kJ compared to 124kJ).

For future development of HEs, an ERS utilising an HFA in a combination with a set of hydraulic motor – electric generator – battery (or supercapacitor) is therefore proposed to maximise the system energy regeneration capacity and reusability. Fig. 35 shows the configuration of the proposed solution capable of harvesting energy from both boom and swing actuators in HEs. A shuttle valve can be employed to manage the flows between the machine actuators. Additionally, a variable displacement motor can be selected to regulate the flow rate according to the system states to enhance the optimal operation of the generator. The recuperated energy can be then stored as mechanical – hydraulic energy within the HFA and as electrical energy within the battery. The generated electricity can be re-used to support the engine via the generator when the actuators accelerate. To maximise the applicability of the proposed system, system optimization by trading-off between the energy capacity, component functionality, sizing and development costs is therefore necessary.

6. Conclusions

This paper presented a comprehensive review of energy recovery technologies developed for HEs. Different types of ERSs have been developed and proved to be effective through simulation and experimentation. Some ERSs have been commercialized and used in nowadays HEs. However, there are still many issues that need to be addressed to meet the increasing demands on high performance – high efficiency HEs. Some conclusions drawn from the paper can be summarized as follows.

The advantage of ERSs using electric storage is that it can quickly recover energy without affecting the operation of the system. The recovered energy can be reused in all actuators where electric power is needed. If EHA(s) are properly employed, the end actuators can be directly controlled by the electric motors(s). Hence, energy losses in the main control valve in the conventional hydraulic system can be eliminated. However, the use of electrical ERSs results in low energy conversion efficiency and increased costs due to the need of hydraulic pump-motor and electric motor-generator. In addition, the use of EHAs could slow down the system dynamics, potentially impacting customer acceptance.

Hydraulic ERSs can overcome electrical ERSs weaknesses such as higher efficiency, lower costs and easy installation within existing hydraulic circuits of HEs. However, the major problem with ERSs using hydraulic storages is that the pressure in the accumulator increases during the recovery process, which prevents the actuators (such as cylinders and swing motor) from operating. Limited volumes of hydraulic accumulators and required installation spaces are also responsible for the reduction in the amount of energy that can be recovered. In addition, the recovered energy in the accumulator requires other ancillary equipment such as pumps or hydraulic motors to be reused.

Similar to hydraulic ERSs, mechanical ERSs could offer high energy regeneration efficiency. However, the critical issues with this kind of systems are known as noises and mechanical frictions between couplings and gears which result in the recovery of energy being reduced over time.

To overcome the above challenges in ERSs, new energy recovery elements combining with optimal management – control strategies are of significant importance. For instance, development of 3-port pump or 3-chamber cylinders could help to simplify and then reduce size of hydraulic ERSs whilst improving the overall performance. Using control strategies based DP or observer could help improve the performance.

In principle, the above energy recovery technologies can be utilized for different actuators in HEs, including boom system (with potential energy through boom lowering) and swing system (kinetic energy through acceleration and/or deceleration). However, dependent on the application purposes, different equipment and control components are required to ensure the system functionality. In addition, energy saving capacity of current ERSs for swing systems are still limited. Hence, the continued development of ERSs especially for rotating systems is essential.

Development of new ERSs utilising multiple energy storage devices which is directly applicable to different actuators in HEs is another trend. For example, combining flywheel-accumulator or accumulator-battery/supercapacitor could help to maximise the energy and power densities of ERSs and subsequently, minimising the machine fuel consumption. Further study to trade-off between energy efficiency, cost, size and durability will help to bridge the gap between the fundamental development and practical applications of ERSs, accelerating their routes to market.

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