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Review of the Energy Saving Hydraulic System Based on Common Pressure Rail

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ABSTRACT Recently, much effort has been directed toward reducing the energy consumption of hydraulic systems against the backdrop of energy shortages and environmental problems. This paper is focused on the development of an energy-saving hydraulic system based on common pressure rail (CPR), which has the potential benefit of being widely applicable to construction machinery. First, the principle of CPR is introduced. Then, the main components, including hydraulic transformers and storage elements, are reviewed, followed by an analysis of the development and research efforts focused on the CPR from a system perspective, which includes energy saving application and control performance investigation. Finally, the challenges and the direction of future development are discussed.

INDEX TERMS Energy saving, hybrid technology, common pressure rail (CPR), hydraulic transformer, hydraulic.

I. INTRODUCTION

In recent years, as a result of energy shortage and environmental impact of inefficient machinery, a topic of much research has been energy-saving and emission-reducing designs for the hydraulic systems used in construction machinery. Such systems, used in applications such as excavators, wheel loaders, etc. [1]–[5] have historically had low efficiencies . Although current industry-standard hydraulic systems have played an important role in increasing efficiency over systems used historically, these systems also suffer from obvious disadvantages. For example, adopting hydraulic valve-controlled throttle governing system will lead to low working efficiency because of unavoidable throttling losses and difficult energy recovery (the hydraulic system efficiency of the excavator is mostly below 30%). Moreover, as a requirement of implementing compound control of multiple actuators by using a single pump, systems utilizing a single variable displacement pump s or those utilizing electro-hydrostatic actuation (EHA, where a variable frequency motor directly drives a constant displacement pump) fails to obtain extensive application [6]–[8]. However, the concept of Common Pressure Rail (CPR) system provides a promising direction for constructing a high-efficiency, modularized and high-reliability hydraulic system [9].

CPR was initially proposed by Innas Corporation, however, its theoretical basis (from the aspect of rotary load control) was similar to the secondary regulation technology, which was proposed in Germany as early as 1977 [10]. The hydraulic system based on CPR can be divided into a high pressure side(HP) and low pressure side (LP), as is illustrated in Fig. 1. It is similar to the electric grid system that has high and low voltage lines. A constant pressure regulating variable displacement pump is selected as the main pump that is integrated with a hydraulic accumulator to guarantee the pressure to be unchanged for HP. Furthermore, the LP is connected to tank. Then, different actuators are connected in parallel between HP and LP. Hence, the control targets such as displacement, velocity or power can be realized by adjusting the displacement of actuators under constant pressure condition. In other words, the working principle determines that the actuator displacements must be variable. Generally speaking, rotary load can be controlled by Variable Displacement Hydraulic Pump/Motor(VDPM), which is similar to conventional secondary regulation. For those hydraulic cylinders

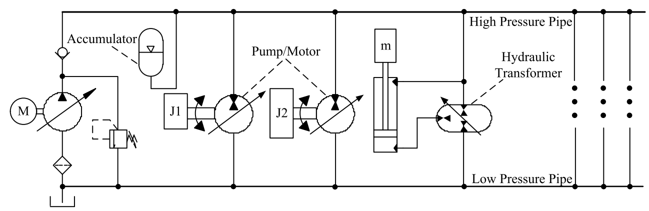

FIGURE 1. Architecture of the hydraulic system based on CPR.

used to drive linear load, because of the difficulty of realizing displacement variables for such actuators, the throttle valve is used according to the traditional method. However, the throttle valve can only be used to reduce pressure in one direction (typically from pump to linear actuator), and secondly, large throttling losses during operation will result in low hydraulic system efficiency. Therefore, a new kind of hydraulic component that can drive linear load without throttle loss is in urgent need for CPR, which is the background for the development of hydraulic transformer(HT). Hence, the throttling loss of the CPR-based hydraulic system is low because valve controlled method has been replaced. Especially, energy recovery can also be realized by using components which can work under all four-quadrants, such as VDPMs and HTs [11]. Therefore, it possesses high efficiency. In addition, a kind of component that can store energy is also needed. For instance, hydraulic accumulator is often chosen while batteries and, flywheels have also been put into application in recent years. Thus, CPR system can be effectively implemented by using the components listed above and the proper control strategy.

In this paper, the state of the art of CPR is analyzed, and the development direction and key problems are concluded from two aspects. The first one is about main components in CPR system and the other one is about its main application. Then, this paper will put forward an active pressure-regulating system, which can improve overall efficiency and save energy with the purpose of being applied in constructing machinery.

II. DEVELOPMENT OF HYDRAULIC TRANSFORMERS

The main components of CPR consist of the main pump, VDPMs, HTs and energy-storage elements. Among them, the main pump is typically an axial piston pump and its development can be referred in [12], this paper will not give a detailed analysis, however, other components will be introduced below.

A. WORKING PRINCIPLE OF HYDRAULIC TRANSFORMERS

The reason for limited application of CPR is the lack of a good solution to drive linear actuators. Hence, the HT is the key component for CPR because it can not only drive the linear or rotary actuators without throttling loss, but can also enable energy recovery from all actuators. The control principle of HT is illustrated by Fig. 2 [13]. For example, in actual working conditions, the task is to adjust system pressure from p_A to load pressure p_B. If the throttling control method is adopted, the pressure should be adjusted according to curve 1, by which the energy loss is calculated as

$$P_{loss} = q_B(p_A - p_B) \tag{1}$$

However, if the HT is adopted, pressure should be adjusted according to curve 2. Provided that internal loss and tank-connecting hydraulic power are ignored, then energy conservation equation should be followed as

$$p_A q_A = p_B q_B \tag{2}$$

We can conclude that there is no power loss from equation (1), in theory. And the relationship between actuator flow and oil source flow can be obtained as

$$\frac{q_B}{q_A} = \frac{p_A}{p_B} = -\frac{1}{\lambda} \tag{3}$$

where λ is the transformer ratio.

Therefore, by changing the flow of A and B, the pressure ratio between oil source and actuator can be controlled. Figure 2 also reveals that when pressure is adjusted according to curve 2, due to the different flow between A and B, a third line T should be added to compensate for the difference between A and B in order to make the inflow and outflow of the HT to be equal. Thus, the HT needs at least three pipelines and then the equation is

$$q_T = q_B - q_A \tag{4}$$

The HT, in nature, adopts the mode of volume control, so there is no throttling loss in theory. Moreover, it can accomplish the transformation from source pressure to load pressure and at the same time, it can recover energy from the actuator and redirect it to the pressure source, thus improving efficiency. Current HT can be divided into two types: One type is Series Hydraulic Transformer (SHT), which consists of two axial piston components rigidly coupled by a common axis; the other one is New Hydraulic Transformer (NHT) proposed by Innas Corporation in 1997, as shown in Fig. 4, which has three oil ports in port plate [14].

B. SERIES HYDRAULIC TRANSFORMER

The SHT usually consists of two independent VDPMs rigidly coupled by a common axis. Its principle can be illustrated in Fig. 3. Equation 2 shows the transformation ratio is

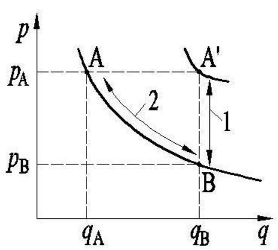

FIGURE 2. Pressure and flow curve of HT.

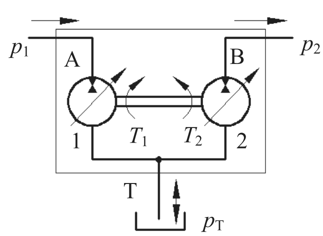

FIGURE 3. Principle diagram of SHT.

FIGURE 4. First prototype of NHT [14].

changed to the equation below because the rotation speed is counteracted.

$$\lambda = \frac{p_B}{p_A} = \frac{V_A}{V_B} \tag{5}$$

where V_A and V_B are the displacements of A and B respectively.

In 1971, H.K. Herbert has put forward a kind of series two-way HT, as is illustrated in Fig. 5 [15]. In Fig. 5, the transformer consists of independent axial piston pump and variable motor. The rotor of pump has machinery joining with the rotor of motor so that the two can rotate together. According to the running conditions of the system, the pump can function to serve as the motor, and so also the motor can change functions to serve as the pump. Therefore, by adjusting the displacement of the variable motor, it can conduct two-way adjustment of the pressure.

In 1982, R. Kordak from Rexroth conducted a theoretical analysis for the connection type between non-variable actuator and hydraulic constant pressure network system [16]. Afterwards, several researchers including K. Dluzik, M. C. Shin, et al made use of the different types of connection between hydraulic cylinder and HT, which included what the dynamic properties of HT would be when actuator load, structure and system parameters changed. In 1996, R. Kordak analyzed the loss condition of secondary adjustment system from the energy aspect. He pointed out that for those systems whose hydraulic cylinder was controlled by HT, its loss was only determined by the efficiency of HT itself under the proper assumptions [17]. In 1997, Dantlgraber put forward a kind of SHT whose structure can be illustrated in Fig. 6 [18]. This kind of HT integrates two piston components into one shell, by which the volume and weight can be reduced and its integration level can be improved. However, the shell and control mechanism need fine matching and difficulty of changing the mature axial piston component is great.

In 2002, Dong from Harbin Institute of Technology(HIT) established an experimental system for simulating lifting apparatus based on the secondary regulated hydrostatic transmission technology, which proved the pressure transformation principle of HT [19]. The experimental prototype is shown in Fig. 7.

In 2014, Li has set up a miniature-piston HT and exploited a trajectory tracking controller based on back-stepping, whose effectiveness has been proved. The prototype is shown in Fig. 8 [20]. Furthermore, the research has taken the effect of HT's rotational speed into overall consideration and established that optimizing the transformer speed can further improve efficiency.

As the SHT rigidly connects the hydraulic motor and hydraulic pump, its volume is large; its structure is heavy and its moment of inertia is large. In addition, as total efficiency is determined by the product ofthe mechanical efficiencies and volumetric efficiencies of two secondary components, the overall efficiency is low and the speed response of secondary components results in the slow speed response for the SHT. All of these disadvantages limit the application of the SHT and the number of institutes researching the SHT is reducing. In conclusion, the development direction is changing towards smaller volumes and lighter units.

C. NEW HYDRAULIC TRANSFORMER

1) WORKING PRINCIPLE OF THE NEW HYDRAULIC TRANSFORMER

Aimed at solving the problems of the SHT, Holland's INNAS Corporation manufactured the first HT prototype which integrated two hydraulic pumps or motors in 1997 and called it the Innas Hydraulic Transformer (IHT) [21].

As is illustrated in the Fig. 9 and Fig. 10, on the basis of bent-axis piston pump or motor, it gets rid of output shaft and makes three oil ports instead of two in the port plate which is connected to HP of CPR, load and oil tank separately.

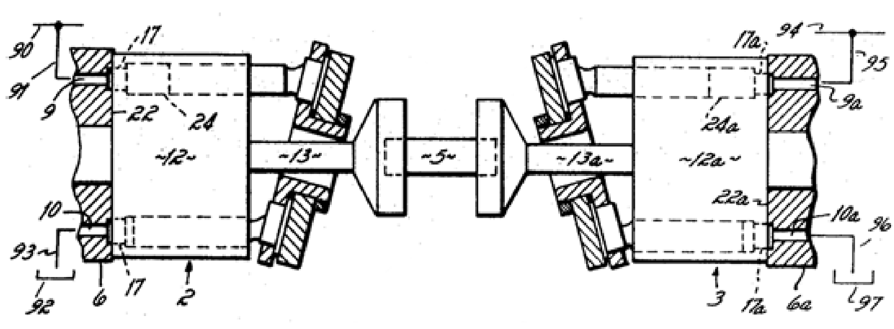

FIGURE 5. Kind of two-way SHT [15].

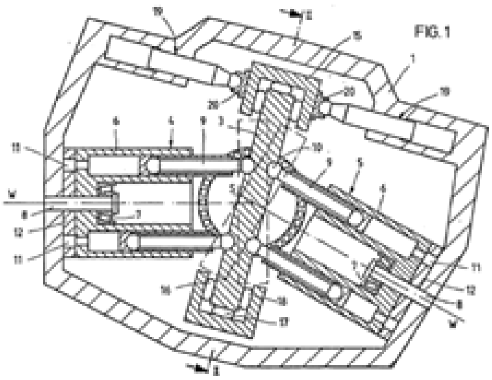

FIGURE 6. Kind of SHT [18].

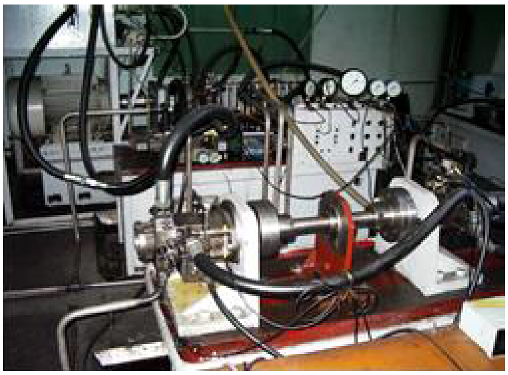

FIGURE 7. Prototype of the SHT from HIT.

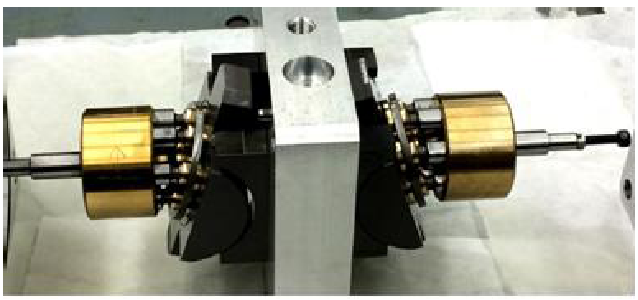

FIGURE 8. Prototype of the miniature-piston HT [20].

Rotational direction and speed of the cylinder block are decided by the sum of the torques at the three ports corresponding to the action of pistons on the swash plate. Equation (6) gives the transformer ratio calculation method, it can be found that by controlling the rotation angle of the port plate, the flow ratio and pressure ratio between load and CPR are changed, thus making it adaptable to load pressure [22], [23].

$$\lambda = \frac{p_B}{p_A} = \frac{-\sin\frac{\alpha}{2}\cdot\sin\delta - \frac{p_T}{p_A}\cdot\sin\frac{\gamma}{2}\cdot\sin(\delta+\frac{\alpha}{2}+\frac{\gamma}{2})}{\sin\frac{\beta}{2}\cdot\sin(\delta-\frac{\alpha}{2}-\frac{\beta}{2})} \tag{6}$$

Where α, β, γ are arc lengths corresponding to A, B and T ports respectively, and δ is the control angle which is the

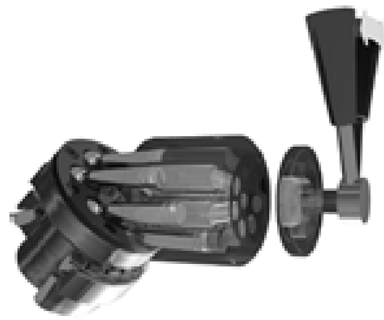

FIGURE 9. Construction of NHT [6].

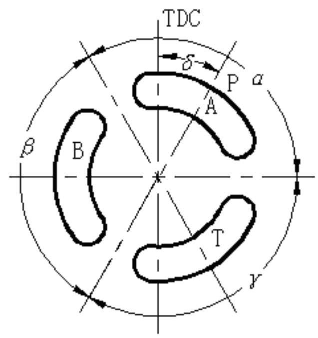

FIGURE 10. Construction of integrated HT valve plate [6].

angular position of the central point P relative to top dead center TDC.

2) DEVELOPMENT OF THE NEW HYDRAULIC TRANSFORMER

This kind of port plate with three kidney slots can be considered as a breakthrough in transformer structure, for it solves the problem of a heavy SHT structure. However, as the kidney slot of the rear cover is the same as that of the port plate, the flow area will be decreased and throttle loss will be increased while rotating [14]. What is more, the range of pressure-regulated rate will be reduced and its efficiency will be poor. Therefore, related organizations all over the world have made corresponding studies and designs, including optimizing the port plate design, reducing noise and pressure pulsation, enlarging the control angle, improving the driving mechanism and elevating the efficiency of variable speed.

a) PORT PLATE OPTIMIZATION FOR IMPROVED DISTRIBUTION

In 2000, Achten and Zhao have optimized the port slots of NHT, in order to balance the force and improve its control properties. They also analyzed the difference resultant from the rotation of the traditional axial piston components and pointed out that the dimensions of the IHT could be chosen properly so that the influence of the coupling between high pressure pipe and load pressure resulted from the rotational angle of port plate was reduced. They also referred to a kind of small-displacement NHT prototype [23]. As is shown in

FIGURE 11. **Port plate and cylinder port matching construction of NHT [23].**

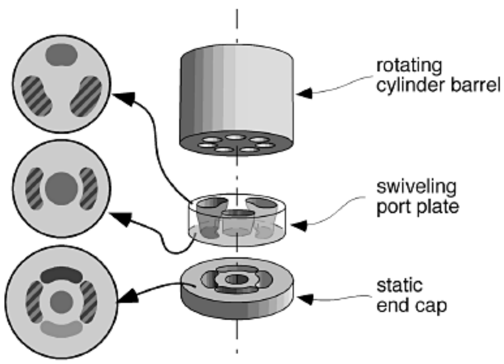

FIGURE 12. **Four-quadrant port plate design.**

the Figs. 11 and 12, it offered a direction to the various application of NHT.

Ouyang from Zhejiang University has performed theoretical studies on energy-saving applications, the design of flow distribution structure, and the flow, displacement and efficiency of NHT. By distributing three port slots in three different radii, there will be no throttle loss while rotating the port plate [24]. The end face of the port plate can be illustrated in Fig. 13 and its prototype can be seen in Fig. 14. The range of its pressure adjustment is between 0 and 1.2. However, this kind of NHT must be adjusted manually, thus enhancing the difficulty of controlling the actuators precisely.

Besides plenty of studies on the optimization of the port plate, Beijing Institute of Technology (BIT) has provided another method, shown in Fig. 15 [25]. Jin, et al. have proposed a HT structure that replaces the rotation of port plate with the rotation of swash plate. There is no longer relative motion between port plate and rear cover by this method and it is remolded based on current mature axial piston pump, therefore, the remolding is easy and of great efficiency.

b) DESIGN FOR REDUCTION OF NOISE AND PRESSURE PULSATION

The methods of reducing noise mainly have been designed for axial piston pumps and motors, such as changing the shape of piston hole and oil port, and increasing the number of pistons [26]–[28]. In addition, according to the exploited structure of NHT, other structures, such as 'shuttle technique' [29], [30] or 'floating cups technique' [31], [32], are also effective ways to reduce noise and pressure pulsation. Through experimental evidence it will be clear that such 'shuttle' technique can reduce flow pulsation and lower noise.

c) ENLARGEMENT OF CONTROL ANGLE RANGE

In 2012, Achten with his group put forward a kind of double-barrels HT. The connection structure between oil port of port plate and its shell becomes easier by adopting double-barrels installed on the same axis and rotating the swash plate to change the pressure. Through the change of the middle swash plate, the control angle of the transformer can be enlarged correspondingly. However, such a design also exhibits some disadvantages, including great flow loss and friction loss.

In order to avoid above problems, IHT has made a recent improvement called 'Oiler Transformer', as is shown in the Fig. 16 [33]–[35].

The three-kidney port plate is mated to a semi-spherical swash block which has three degrees of freedom. Due to the introduction of such a new port plate with spherical bearing, the extra rotary angles can operate the transformer in a larger range. However, the whole structure is complicated, and the possible friction and loss between swash block and support surface. In addition, the problem of how to regulate the rotation of swash block to operate actuators is one that is yet to be solved.

d) IMPROVEMENT OF DRIVING MECHANISM

In order to realize the electric closed-loop control, the driving method for rotating the port plate is also a topic of much research. In 2008, Dr. Lu has designed a hydraulic

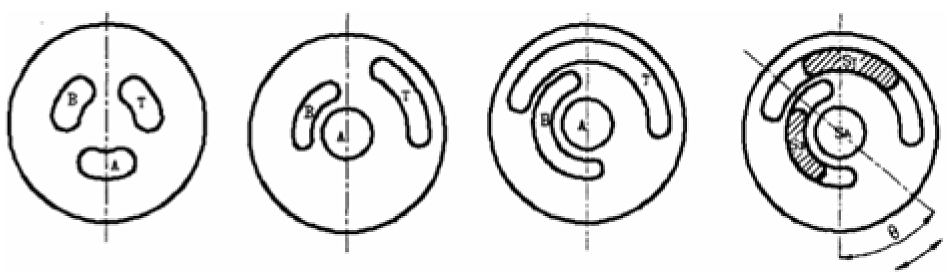

FIGURE 13. **End view drawing of the port plate.**

FIGURE 14. Prototype of the manual control NHT from Zhejiang University.

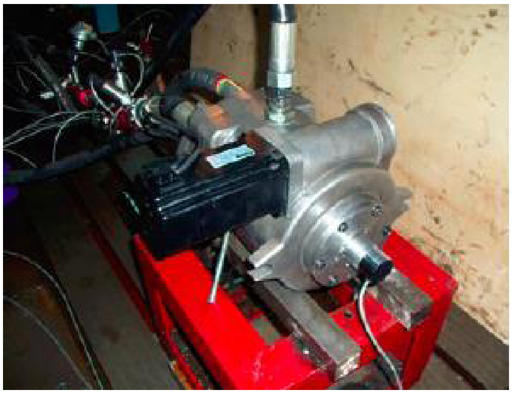

FIGURE 15. Prototype of the NHT from BIT.

transformer called HHT1 with a servo motor driving the port plate that rotates based on AF2 fixed displacement motor [36]. As is shown in Fig. 17, gears are manufactured on the outer ring of swash block which mate with small gears fixed onto the principal axis of the servo motor. Through the control of the servo motor, the rotating angle of port plate can be controlled, thus making it possible that the transformer control for the actuators becomes closed-loop control. However, the driving torque of the servo motor is small and it is easy to overload it, and in such a case the actuator response speed will be slower.

In order to solve the problems existing in HHT1, HIT has exploited HHT2 which is updated from one swash-plate axial piston pump as shown in Fig. 18 [37]. The novel feature is adoption of swing cylinder to control the rotation of port plate directly. Therefore, in HHT2, the control of rotating angle is transformed into the servo cylinder controlling the swing cylinder, which possesses the merits of fast response, high control precision and easy integration with the existing engineering machinery.

e) IMPROVEMENT OF OVERALL EFFICIENCY UNDER DIFFERENT SPEEDS

As most NHTs are designed based on axial piston components, how to enable conventional axial piston components to maintain high efficiency across actual working conditions is also an important topic of research. What is worth special mention is that NHT is often under the condition of variable rotational speeds while working, and thus increasing the efficiency of during low rotational speeds is a key problem to be solved. It could be found that the efficiency has a large difference under different rotation speeds.

Actually, the five points above are not separated from each other, they have intersections among themselves. Therefore, when ameliorating one of the above issues, other aspects should also be considered.

III. SELECTION AND DEVELOPMENT OF ENERGY-STORAGE COMPONENTS IN CPR SYSTEM

A. ANALYSIS AND COMPARISON OF DIFFERENT ENERGY-STORAGE COMPONENTS

One of the main advantages in CPR is that energy recovery can be realized. The working principle of CPR utilizes the four-quadrant operation of VDPM or HT to recover the actuator-supplied energy (either kinetic energy during the braking of large actuators, or potential energy from gravity) and store the energy. The stored energy will be released and reused, instead of being dissipated as heat. Thus, how to recycle the energy and store it becomes another important issue.

At present, some examples of the various energy storage methods are the storage battery, the hydraulic accumulator,

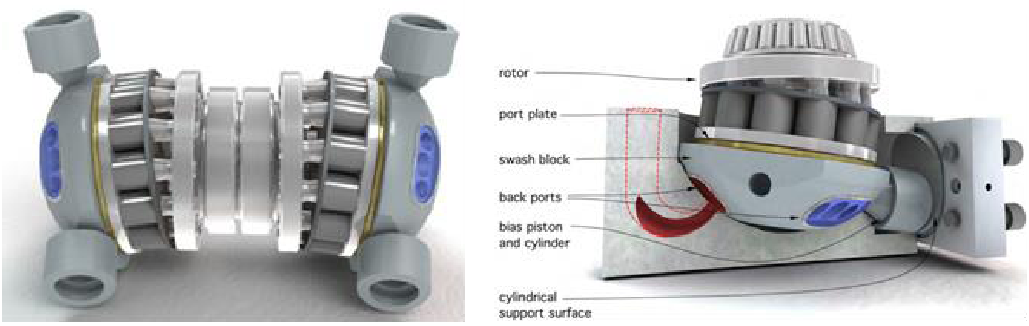

FIGURE 16. Structure of 'Oiler Transformer' [36].

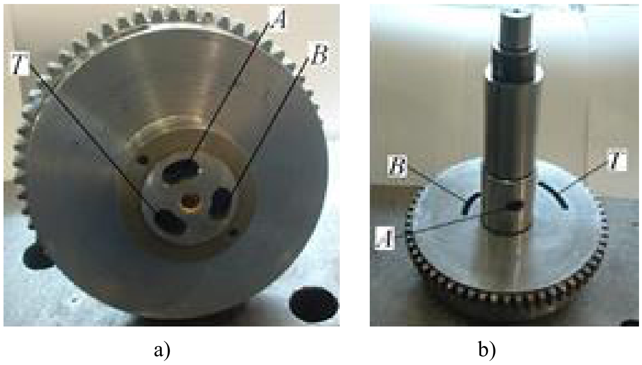

FIGURE 17. Construction of port block. a) Main view of port block. b) Rear view of port block.

the flywheel and the ultra-capacitor. A comparison between them is revealed in Tab. 1 [38]–[41].

The energy density and power density are the two most important parameters for energy storage units, as the comparison curve shows in Fig. 19. Each of the four kinds of energy storage devices have their own advantages and disadvantages. From Table 1, hydraulic accumulators possess the largest power density which reaches 19kW/kg, while batteries are the least. Therefore, energy storage units should be determined according to actual working condition.

As the main application for CPR system is construction machinery and large engineering vehicles which need large amounts of instantaneous power delivered to actuators, high power density is a top requirement from the energy storage device. In addition, the efficiency of energy conversion is another important factor to be considered. Considering the above two factors, the hydraulic accumulator is preferred because it possesses high power density. Moreover, it does not need to transfer hydraulic energy into another form of energy while adopting the hydraulic accumulator in CPR, thus improving efficiency of energy conversion. However, the disadvantage is the low energy density, which means that if there are large amounts of energy to be stored, more accumulators are needed. This creates installation space difficulties in the application of multiple hydraulic accumulators in construction machinery.

B. DEVELOPMENT OF HYDRAULIC ACCUMULATOR AS ENERGY STORAGE UNITS IN CPR

Currently, there are three important aspects for the development of hydraulic accumulators as energy storage units in CPR.

1) IMPROVING THE STRUCTURE OF HYDRAULIC ACCUMULATOR

Hydraulic accumulators for energy recovery are components that need to be installed in addition to the existing hardware on traditional hydraulic systems. Hence, the added weight and volume can also increase the energy consumption,

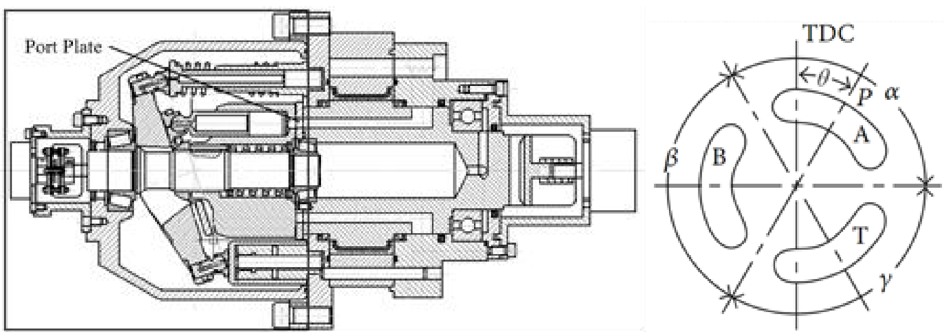

FIGURE 18. Structure of HHT2.

TABLE 1. Comparison of different energy storage units [38].

	Lead batteries	Flywheel	Ultra capacitor	Hydraulic accumulator
Energy-storage form	Electrochemical	Mechanical kinetic	Electric	Hydraulic
Power density(kw/kg)	0.2	0.5-11.9	1	19
Energy density(Wh/kg)	65	5-150	10	2
Efficiency	~80%	~90%	~90%	~90%
Energy release rate (DoD)	~75%	~95%	~100%	~90%
Life span (year)	2-5	>20	>20	~20
Environmental property	Poor	Good	Ordinary	Ordinary
Maintainability	Good	Medium	Good	Medium
Degree of sophistication	Mature	Ordinary	Ordinary	Mature

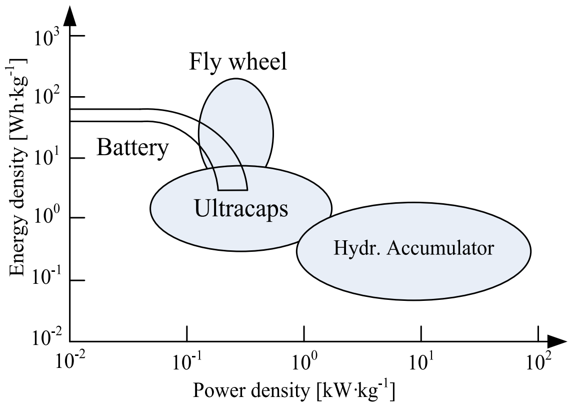

FIGURE 19. **Comparison between energy density and power density for different units [38].**

especially during linear motion of construction machines. In order to solve this problem, advanced material and manufacturing technology have been applied in designing the hydraulic accumulator in recent years. High stiffness and high strength carbon fiber materials are involved by using filament winding method to reduce the weight of hydraulic accumulators [42]. The use of alternative materials, such as aluminum, is another means of reducing the weight of accumulators [43]. Moreover, some manufactures have introduced special series of accumulators for hybrid systems which have reduced-weight accumulators and double piston structures among other innovations [44].

2) MULTIPLE ENERGY- STORAGE COMPONENTS FOR A SINGLE APPLICATION

In order to combine the advantages of different types of energy storage components, researchers have tried the method of adopting several energy storage units together. Achten has proposed an architecture for hybrid passenger vehicles that can take advantage of the high energy density of batteries and the high power density hydraulic accumulators, which is shown in Fig. 20 [45].

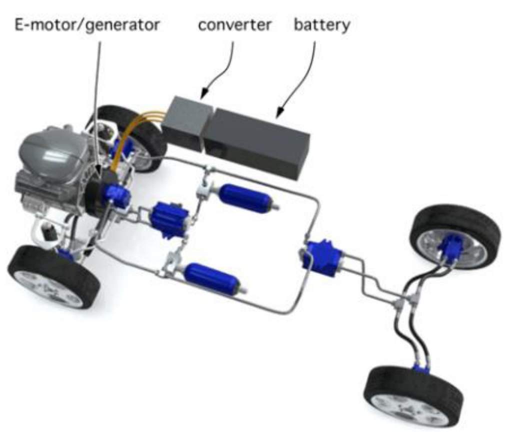

FIGURE 20. **Hybrid vehicle architecture using two kinds of energy storage elements [45].**

Lin and Wang have also proposed a method of integrating the hydraulic accumulator and battery together [3]. They applied such a technique into the potential energy recycling system for the arm of excavators, as is shown in Fig. 21. The hydraulic accumulator can recover energy quickly and large amounts of energy can be stored in the battery, thus integrating the advantages of both the accumulator and the battery. Although this system is different from the CPR system, the principle of energy storage is worth noting for reference. Admittedly, this system increases the losses due to energy conversion from one form into another and reduces efficiency of recovery. Therefore, it is important to take the efficiency of recovery into overall consideration.

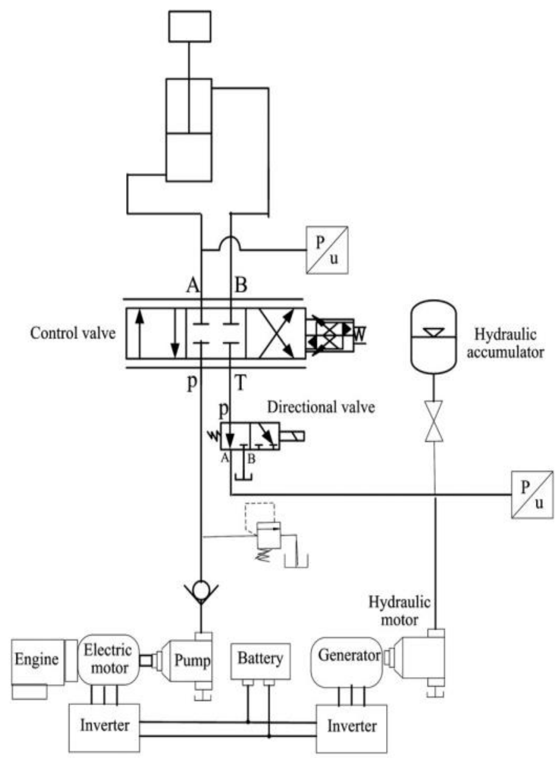

FIGURE 21. **The schematic of the proposed energy regeneration system [3].**

3) CHANGE THE UTILITY OF HYDRAULIC ACCUMULATOR

Considering the engine performance, the traditional role of the hydraulic accumulator, which is restricted to store recovered energy from actuators, is changed in the CPR. In the CPR, it can balance the loads and adjust the operating points of the engine, while the limitation of low energy density will be mitigated. This implies that, when designing the CPR system, obtaining the largest amount of energy recovery is not the sole criterion [46]–[48]. The hydraulic accumulator should be sized so as to allow the engine to operate at high-efficiency points as often as possible, in order to improve overall efficiency.

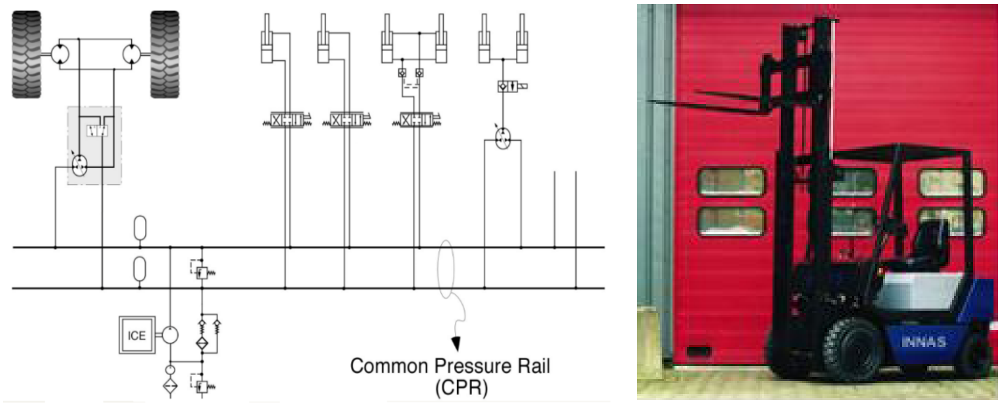

FIGURE 22. Schematic of the forklift system based on CPR [49].

IV. CURRENT APPLICATIONS OF THE CPR SYSTEM

The advantage of CPR system lies in energy savings and modularization, through the ability to retain high power density of the hydraulic system, elimination of throttling loss and energy recovery from actuators. Moreover, the CPR system can realize the independent control of the parallel actuators. Therefore, a large number of research institutions have launched the investigations into the specific application of the CPR, which can broadly be divided into investigations into energy savings and into control performance.

A. CPR FOR ENERGY EFFICIENCY IN MOBILE APPLICATIONS

In 1998, G.E.M. Vael presented a forklift hydraulic system using the CPR, as is shown in Fig. 22 [49]. It used the HT to realize the energy recovery objective for the lift subsystem. This system has simpler and more flexible structure compared to the system based on load sensing. In addition, the paper analyzed the situation for applying HT. If some cylinders are only used occasionally or consume little energy without requiring to higher pressures, a throttle valve with simple structure and low price can be chosen to control such cylinders rather than using the HT.

In 2003, Ouyang et al. investigated the energy saving potential of the HT in a hydraulic elevator system, as is illustrated in Fig. 23 [50]. Based on the working principle of the series HT, they put forward a new kind of hydraulic elevator control system, whose installed power is only one-third to that of ordinary system.

In 2004, Mitsubishi Corporation in Japan has applied CPR technology to public buses and light trucks [51]. As is revealed from the results of trial operation in Tokyo, exhaust gas emission and fuel consumption are both effectively reduced by over 20% compared to current architectures in buses and trucks. In 2007, INNAS Corporation has proposed a passenger vehicle architecture based on CPR, as illustrated in Fig. 24 [52]. The architecture adopted four pump/motors, one at each wheel, and totally eliminated the mechanical transmission and utilizes the HT as a control unit to control four constant displacement pump/motors. As a result, the engine is mechanically uncoupled from the wheels and always works in the highest-efficiency regions, thus improving fuel efficiency and reducing exhaust emissions.

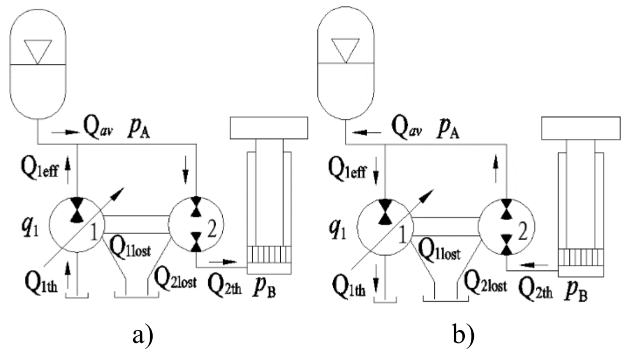

FIGURE 23. Traditional HT applied in hydraulic lift. a) Rising working condition. b) Descending working condition.

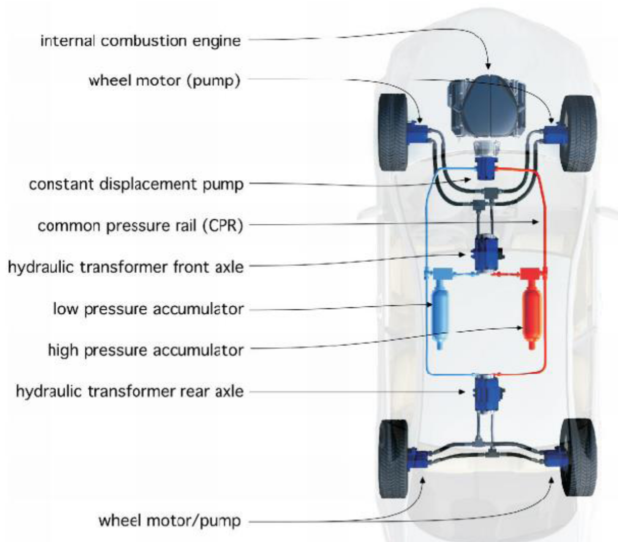

FIGURE 24. Schematic of the hybrid hydraulic car from INNAS [52].

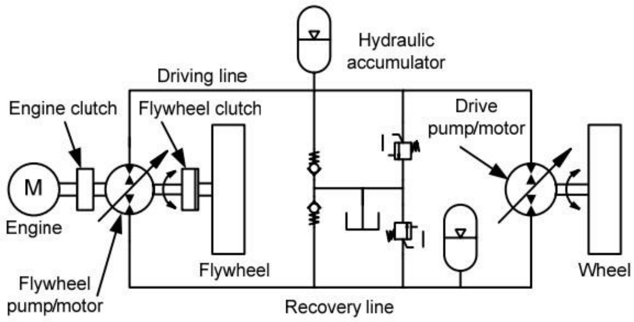

FIGURE 25. Architecture for hydraulic hybrid vehicles [53].

Besides, braking energy will be recovered and stored in an accumulator to provide peak power, so the installed power of engine can be lower. Relative analysis has revealed that a mid-sized sedan can reduce 50% of the fuel consumption and CO_2 discharge of it will be reduced to 82 g/km, which is far below the 120 g/km mandated by the 2012 European Union standards.

In 2008, Kyoung-Kwan Ahn from University of Ulsan has investigated a kind of switching-type hydraulic hybrid car that integrates a flywheel and an accumulator to store energy, the architecture of which is shown in Fig. 25 [53]. In addition, investigations on how to reduce the pressure fluctuation in the high pressure pipe and to lower system noise were also carried out in great detail.

Celestine N. Okoye established the model of oil-manufacture equipment and conducted simulation experiments based on the CPR according to the periodic operation of the palm kernel oil manufacturing equipment, the recovery efficiency of which can reach 97.1% [54]. In 2009 and 2010, Wang and Jiang established a test rig to replicate a hybrid hydraulic vehicle architecture based on the CPR system. Sun proposed a method to optimize the configuration for the series hydraulic hybrid vehicle architecture by adopting the simulated annealing algorithm [55], [56]. Different weight coefficients can be adjusted according to different demands, thus achieving the optimization, and enriching the design method of hybrid hydraulic vehicles based on CPR. In the same year, Zhao applied the CPR system for the aircraft tractor and proposed an algorithm that can improve speed control performance [57]. They conducted relative experiments in simulation, the results of which lay a solid basis for the application of the CPR system to the aircraft tractor.

From 2000, Georges E.M. Vael presented the hydraulic system based on CPR for excavators, then Sebastian Sgro analyzed the energy consumption details for the linear actuators of a 30-ton class excavator, whose schematic is shown in Fig. 26 [58]. The simulation results in Fig. 27 have shown that for the load cycle of the excavator, only recovery of the boom energy is feasible, because about 14 % of the primary energy can be recuperated. The described procedures for the HT system lead to a total energy saving of 37 % compared to a conventional load-sensing system.

B. INVESTIGATIONS ON THE CONTROL PERFORMANCE OF THE CPR SYSTEM

The two kinds of actuators in the CPR system can be divided into the VDPM and the hydraulic cylinder. For the control of

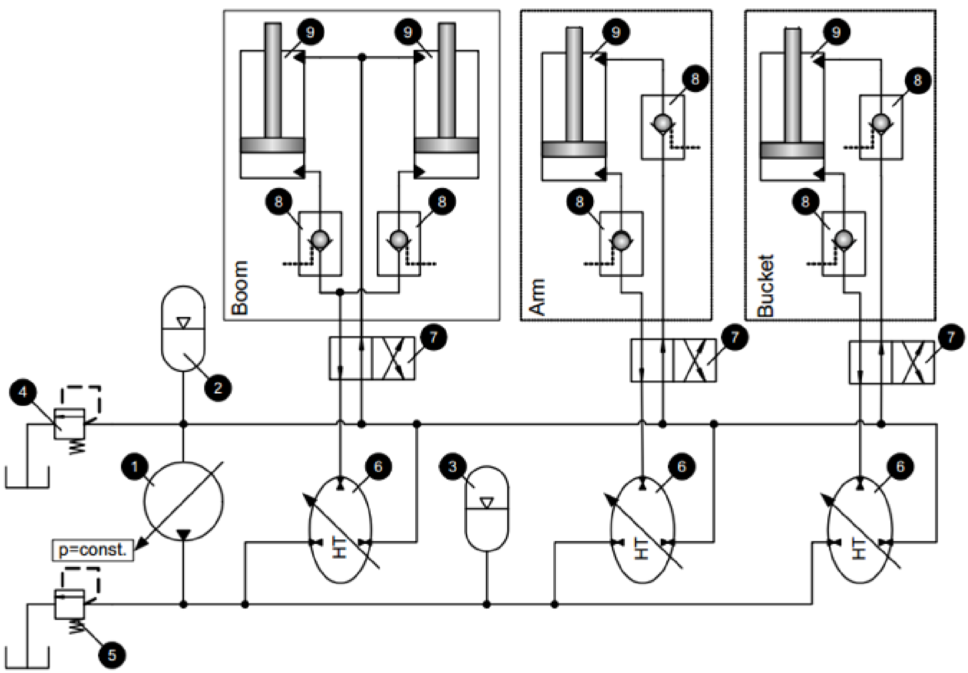

FIGURE 26. Hydraulic schematic for a 30-ton class excavator using CPR system [58].

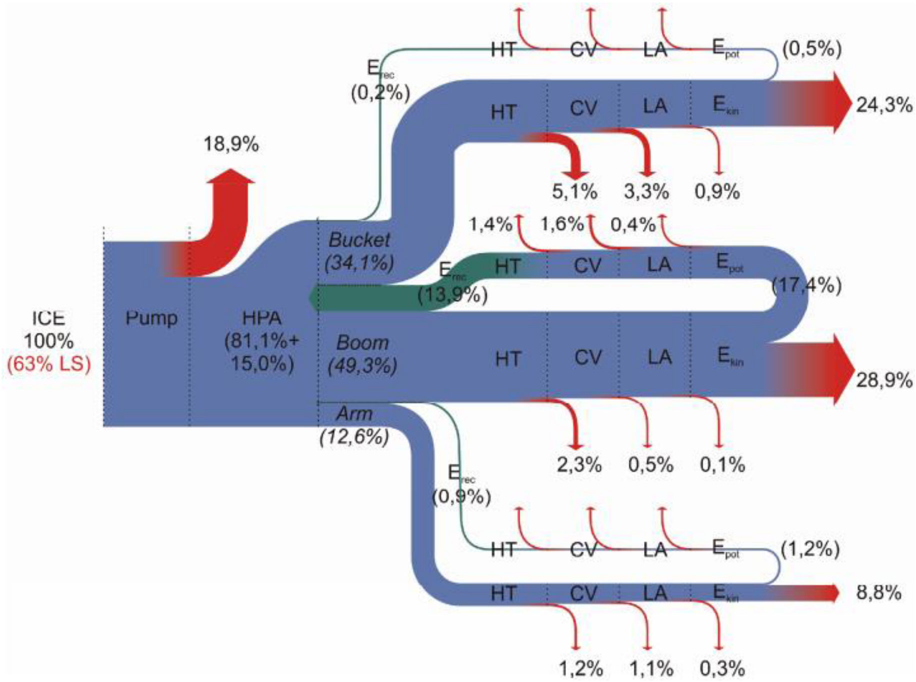

FIGURE 27. Sankey diagram of the HT-based CPR system with Energy Recovery [58].

the former, it is similar to 'secondary control' system raised in H. Nikolaus's patent from 1977. The sole control variable is the displacement of the VDPM, while for the latter the control variable is the transformer ratio of HT which is a new type control mode compared with the traditional hydraulic system [59].

In 1999, Berg has designed a frequency-domain linear robust controller to improve the velocity response and positional accuracy of VDPMs. The proposed controller also provided an effective method of solving the low-speed stability problem [60] (that typically manifests itself in terms of limit-cycles). Weishaupt has introduced adaptive control theory for the control of VDPM. However, as a result of not integrating a proper observer, the actual controller is similar to series proportional controller. Soon afterwards, Yao used the method of combining self-adaption and feed-forward compensation together to improve control performance [61]. Moreover, H. Murrenhoff has investigated several linear controllers, however, most of them focus on the classical method of low-frequency bandwidth [62]. In addition, the stability precision will be reduced when the variation of the load is large. Using the integrating integrator, steady accuracy can be improved, but the limit cycle and integral windup will arise. Subsequently, Sun has achieved the target of suppressing the disturbances to the system by adopting a control method based on quantitative feedback theory [63].

In 2005, Ma has investigated a position control method wherein the HT drives double-action cylinders, and the principle of which can be illustrated in Fig. 28 [64]. Ma achieved position control effectively by relying on a

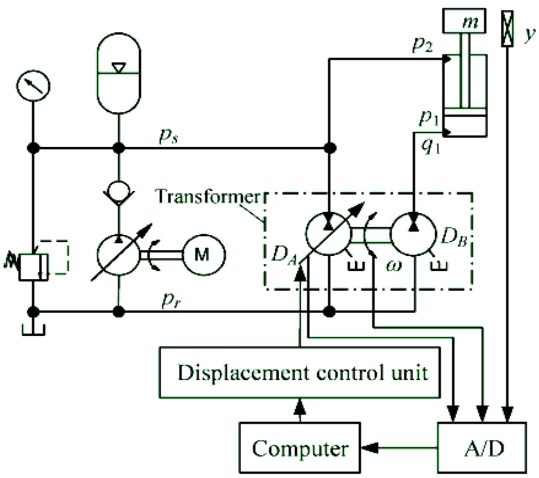

FIGURE 28. Principle of cylinder position control system with HT.

robust control strategy, and thus improving the rapidity and accuracy of position control. Kyoung Kwan Ahn also has performed a comparative study of using SHT to drive hydraulic cylinders within the CPR system. He has made comparative research on single-acting connection and double-acting connection and studied position control based on PID control [65].

Shen has adopted the method of combining observer design and robust control algorithm to conduct a research on the system of hydraulic pump/motor velocity control based on CPR, considering the condition of bounded disturbance and sensor fault. Compared with PID control, it improves the robustness

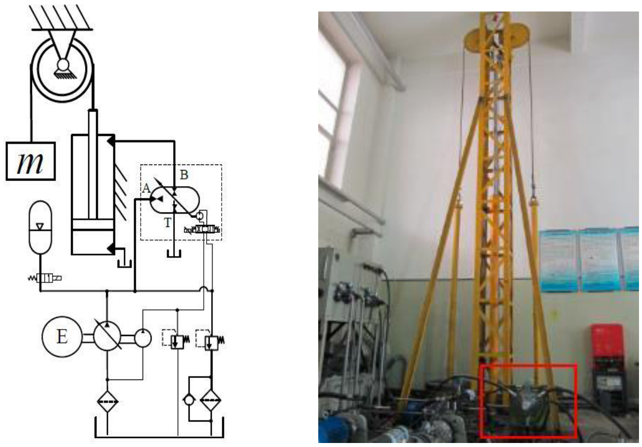

FIGURE 29. Principle of cylinder position control system with NHT from HIT [67].

of velocity control [66]. However, the research is only aimed at accurate model, leaving the effect of the parameter uncertainty. In 2014, Shen has analyzed the dynamic performance of boom cylinder which is controlled by NHT, as is shown in Fig. 29 [67], [68]. He pointed out that state variables of system are inter-coupled and the controlled variable, which is the rotating angle of port plate of NHT, is in trigonometric functions. As the state variables of system are restrained by actual variable limit, the system is a strong coupling nonlinear system that possesses input saturation properties. As a result, the control difficulty is great. By simulated analysis, Shen pointed out that the upper limit of control angle should be about 1.75rad and the efficiency of HT will be dramatically reduced if the angle of port plate is increased for the sake of excessively large transformer ratio. At the same time, he solved system coupling and nonlinear problem based on fuzzy control theory and by the experiment, he proved the effectiveness of the algorithm. However, the result of the experiment, meanwhile, demonstrated that the response of the HT system was slow and advanced control algorithm should be integrated for optimization.

V. CHALLENGES

After comprehensive analysis of the existing literature, it was found that there are several researchers focusing on the structure of the components and the control performance of the actuators based on the CPR system. Though the CPR offers considerable advantages over traditional hydraulic systems, it has not been applied widely. The challenges can be concluded as follows.

A. THE EFFICIENCY PROBLEM OF MAIN COMPONENTS

For the state of the art, hydraulic cylinders could not be replaced to drive the linear load in hydraulic system from the practical aspect. Hence, the development of HTs, which can control both cylinders and motors without throttling loss, decides whether the system based on CPR can develop extensively. However, the key problem restricts the development of HTs includes self-efficiency and control issues.

The efficiency of SHT is limited by multiplication of the efficiency for two components, thus the efficiency is hard to enhance. In addition, the large volume also limits its application. Current SHT is developed towards the direction of light weight, small-displacement and high rotation speed. For NHT, due to its creative three oil ports structure, its volume is reduced dramatically. However, a series of problems resulted from the added rotational freedom between port plate and distribution structure have become a new challenge. The relative researches have shown that if the rotational freedom between port plate and distribution structure is removed, the control accomplished by rotating the swash plate will be a worth researching direction. Based on this principle, the design difficulty of the three oil ports and distribution structure will be lower and the design experience of traditional axial piston component can be learned. However, it is a hard problem for traditional axial piston component to design a rotating swash plate, which also needs to take the way of driving swash plate to rotate into consideration. Moreover, how to resist the acting force that is slippery boots to swash plate so that the rotating angle can be controlled accurately and closed-loop control of variable pressure can be accomplished. If the precise control of rotating the swash plate can be solved, there will be a great push for the development of such structure.

B. CONSTANT PRESSURE REQUIREMENT ISSUE OF HIGH PRESSURE PIPE

The pressure variation of high pressure pipe in CPR is mainly resulted from energy recovery which makes pressure increases and the instantaneous large flow rate requirement is also contributing to the pressure fluctuation. Ideal CPR system expects oil source to supply constant pressure source, however, this kind of ideal constant pressure oil source is hard to realize in practical. In another word, it needs the system to pay high even unaffordable cost when supplying ideal pressure oil source. In addition, although maintaining constant pressure state can lower the difficulty of designing the actuator controller, it means the actuator should work among different displacements to adapt the changing load. However, the efficiency of variable components varies greatly with the working condition which should also restricts the total efficiency.

For example, a 18ml/r axial piston pump/motor, under the premise of the same differential pressure and rotary speed, the volume efficiency will decline from 0.92 to 0.31 corresponding to 100% and 50% displacement, respectively, as is shown in Fig. 30 [69]. On the condition of outputting the same torque, 'constant pressure' will limit the component to adjust degree of freedom when working. Therefore, 'constant pressure' will inevitably give rise to low efficiency of the working components and affect machine energy consumption.

C. COUPLING CONTROL AND INDEPENDENT CONTROL OF MULTI-ACTUATORS IN CPR

As a result of the special coupling properties of 'flow field-power field- temperature field' in hydraulic system, loads of

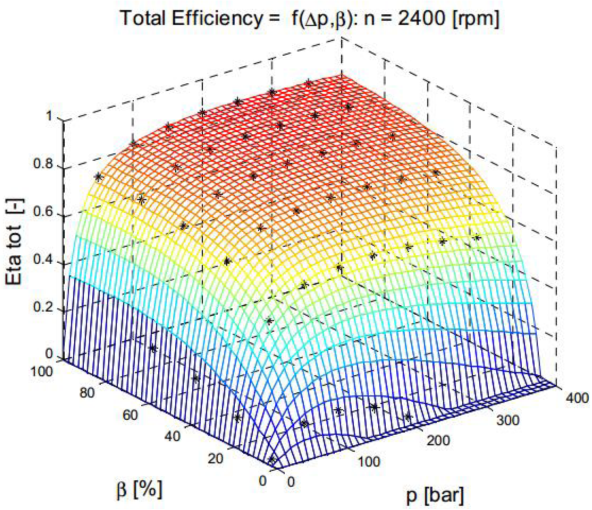

FIGURE 30. Comparison of total pump efficiency [69].

different properties will inevitably affect system while working [70]–[72]. When overlapping nonlinearity of hydraulic components, perturbation of hydraulic system parameters and uncertainty of load working condition, it is hard for CPR to realize the precise compound control of multi-actuators, which is another key factors that limits the extensive application of such a system. Hence, new control methods should be investigated in the future [73]–[75]. Then, the main difficult points are:

1) The controlled objects of two kind of actuators can be concluded as the displacement of VDP and the port plate rotating angle of NHT. In the design of the controller, the two quantities should meet the bounded constraint of variable range.

2) The construction machinery and industrial equipment with periodic working condition tend to have the loads that vary frequently and dramatically, these disturbance variables of which will increase the control difficulty of the system.

3) The kinetic equation of the hydraulic system exits essential nonlinearity. After linear modeling for it, nonlinear characteristics still should be taken into consideration. In addition, several parameters are of uncertainty, such as, effective bulk modulus and the variation of rotational inertia.

VI. CONCLUSION

In this paper, the development of CPR, including the components and system applications, was outlined. It has been established that this system has a large energy-saving potential because it can recover energy and work without throttling loss. However, the development of the key component— the hydraulic transformer — restricts the application range, for it is not widely applied. Then, compared with the SHT, NHT has the advantage of smaller volume, simper structure and faster response. In addition, the distribution structure design and control-angle regulation are the essential issues for NHT. It can be anticipated that, with the development of the HT, the CPR system could be one promising architecture for construction machinery in terms of energy consumption.

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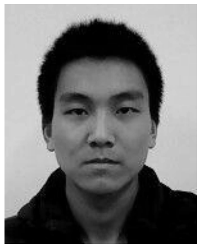

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