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Independent Metering Valve: A Review of Advances in Hydraulic Machinery

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Abstract: In light of the environmental challenges, energy-saving strategies are currently under investigation in the construction industry. This paper focuses on the energy-saving method used in the hydraulic system based on independent metering (IM) technologies, which can overcome the lost energy at the main control valve of the conventional electrohydraulic servo system. By scientifically arranging the proportional valves, the IM system can individually control the flow rate of the inlet and the outlet ports of the actuators. In addition, the IMV system can be used to effectively regenerate energy under different operating modes, thereby saving more energy than conventional hydraulic systems. Therefore, the IMV system has a great potential to improve the energy efficiency of hydraulic machinery. The overall IMV system, including the configuration, proportional valve, operation mode, and the control strategy is introduced via state-of-the-art hydraulic technologies. Finally, the challenges of IM systems are discussed to provide researchers with directions for future development.

1. Introduction

Hydraulic machinery has been an important contribution to human life and applications ranging from constructional to industrial, military, aerospace, etc. However, hydraulic machinery consumes a lot of fossil fuels and emit harmful emissions into the environment. Therefore, reducing emissions and energy consumption on hydraulic machinery is a necessary issue today. To solve these problems, many technology are developed to improve the energy efficiency of hydraulic machinery [1-24]. Some technologies of energy-saving have been proposed to reduce throttling loss and improve the system overall efficiency. Cho et al. proposed to integrate the position tracking control in the valve-controlled cylinder system and energy-saving control in the electrohydraulic load-sensing system. The system can save input energy while maintaining position tracking control accuracy [25]. Ahn et. al developed a novel energy management strategy for a PEM Fuel Cell excavator with a supercapacitor/battery hybrid power source[26-29]. A rule-based energy management strategy increased the efficiency of fuel cell systems and extended the lifetime of power components[30]. Besides, a novel boom energy regeneration system using a variable hydraulic motor proposed by Xiao et. al. The variable hydraulic motor was installed in the return line of the boom system and the regenerated energy was stored in battery or super capacitor through the inverter [31-33]. The energy regeneration efficiency could reach up to 57.4%. However, they just focused on the energy regeneration problem and did not consider the energy loss phenomenon in the hydraulic system.

Many components caused of energy loss in the hydraulic machinery, such as pumps, pipes, and valves. Among them, the energy losses in pump, hydraulic pipe

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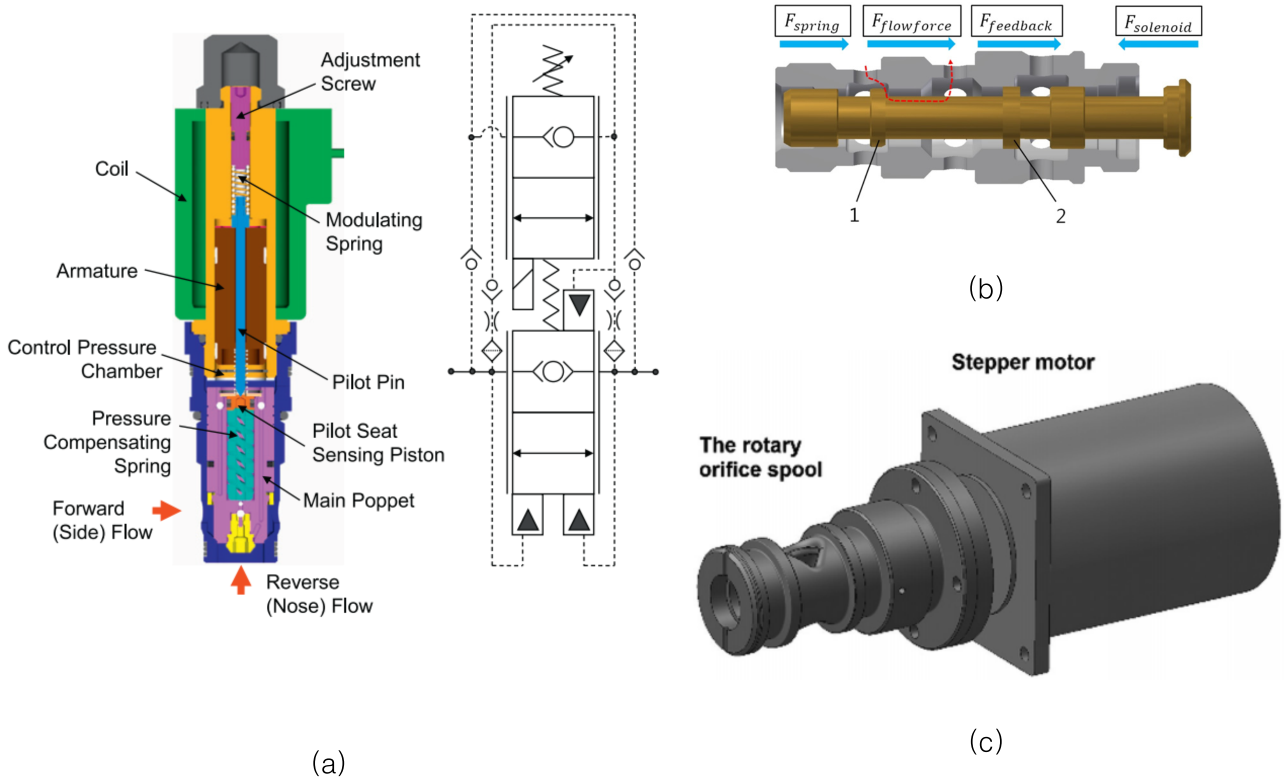


1.1.1. Fig 2. (a). Schematic diagram of the electro−hydraulic poppet valve[75]. (b). Spool in the EPPR valve[76]. (c). Stepped rotary flow control valve[77].

and valve were 19%, 4% and 29%, respectively[34]. The energy losses in pumps and pipelines are difficult to reduce by improving the hydraulic control system because these losses always caused by leakage and friction from these components. Therefore, improve the valve has been a good method to reduce energy loss in hydraulic machinery. In this case, the independent metering valve technology is one of good method to overcome these problems.

The Independent metering valve (IMV) was introduced by Aardema and Koehler[35] with the hydraulic circuit configuration used four proportional valves, electronically controlled proportional valves to control flows within the hydraulic circuit. Two of the proportional valves were disposed between the input port of the cylinder. The other two proportional valves were disposed between the output port. Because of the electronic proportional control valve, the performance of the hydraulic circuit could be modified by adjusting a control signal to each valve. The IMV has been referred to the opportunity of separate control of the inflow and outflow at the hydraulic cylinder ports. The scientific arrangement of proportional valves opens up for differential modes of operation of the hydraulic cylinder. The system can regeneration the free flow in many variants depending on the valve structure. Therefore, IMV technology has the potential to improve the energy saving for hydraulic machinery with the following overall potentials[17, 36-39]:

- Independent control of inlet and outlet orifice.
- Energy is regenerated by energy-efficient operating modes, reduce the throttling loss and energy consumption.
- Control stability of cylinder velocity and position.
- Multiple operating modes.
- Flexible system configuration.
- Advanced control features (oscillation damping, etc.).

With the above advantages, IMV system is interested and researched by many scientists with the aim of saving the best energy on hydraulic machinery. There are many new configurations and methods proposed with the aim of improving the energy performance of

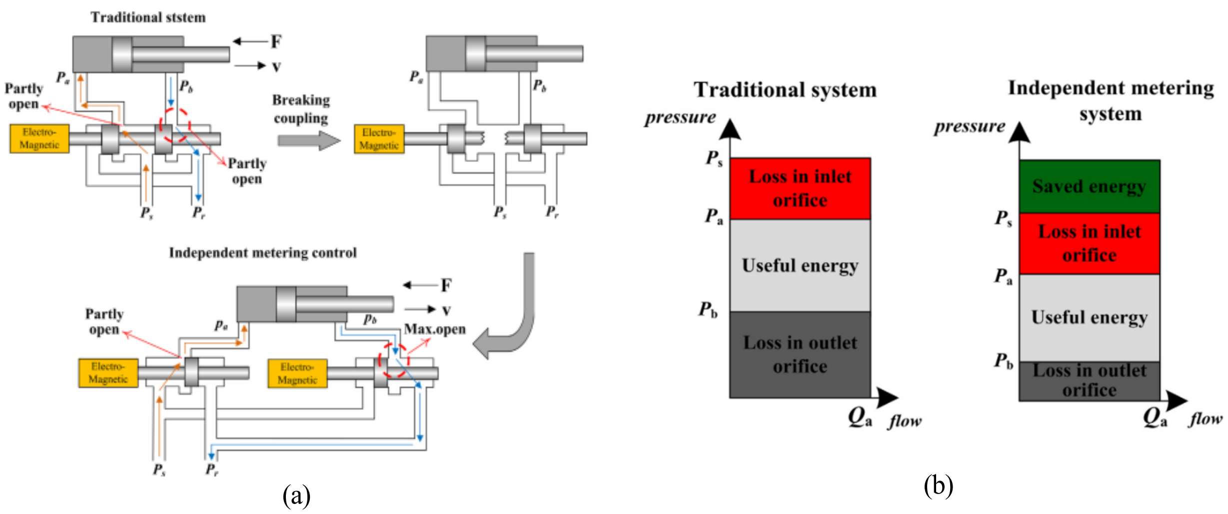


Fig. 1 (a). Schematic diagram of the conventional IMV system. (b). Comparison of energy consumptions[72].

!the system and stably operation[40-45]. However, IMV still have the drawback, such as:

- High cost for the IMV system.
- The complex control method.
- The switching mode operation causes a sudden change in the velocity.
- The difficulty of pressure compensator integration and produces velocity oscillation.

Research on IMV system usually is focused reduce the number of proportional valves in the system and the control method for valve and pump with various approaches. Some studies improve the hydraulic circuit configuration of the proportional valve[46-57] such as the programmable valve, new configuration IMV, etc, Besides, some studies propose the controller to control the velocity and position of the IMV system[58-67]. Thereby, reduce the cost and find optimal control methods for the system. Based on these researches, the IMV system has great potential for application in hydraulic machinery[47, 68-71]. In this review, we introduce aspects and overall evaluation of the independent metering valve system. These aspects include the configuration, valve, operation mode, control strategy and challenges faced by the system. The review starts by reviewing the technologies for saving energy and introducing the IMV system. In Section 2, we will describe the IMV system, proportional valve, advantage and disadvantage. The operation mode and switching mode are discussed in Section 3. Section 4 shows the configuration important and the control strategy of the IMV system. discussion of the challenges is contributed in Section 5. Finally, the conclusion of the paper is presented in final section.

2. Conventional IMV system

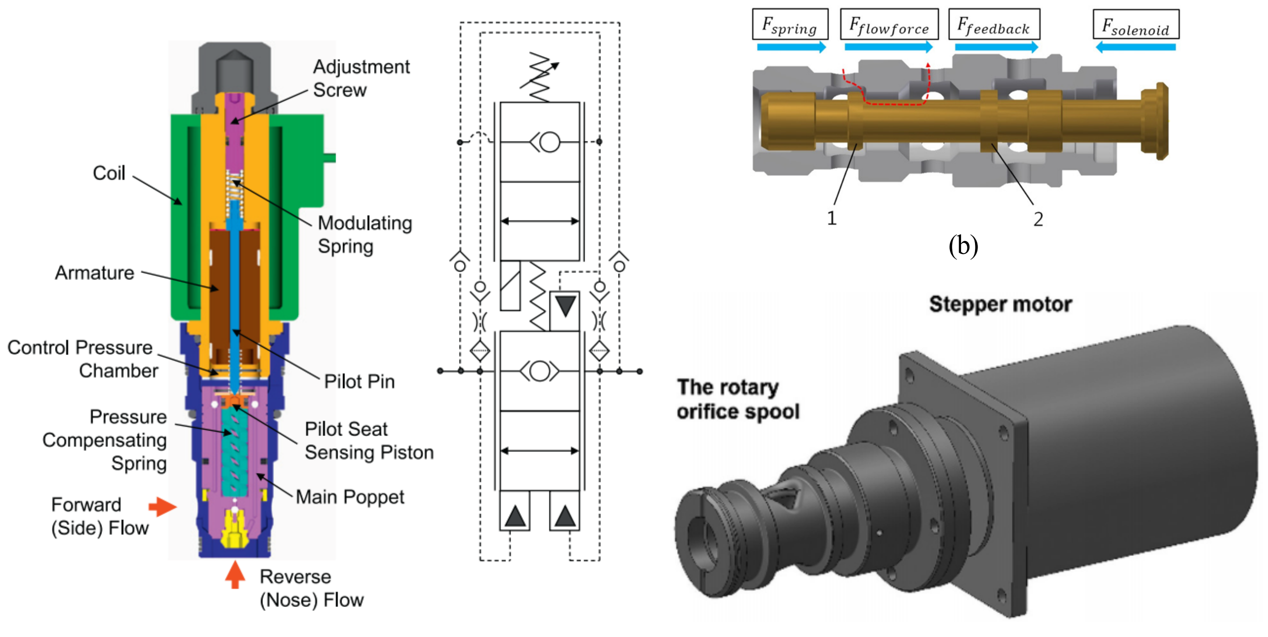
2.1 The conventional IMV structure

The electrohydraulic servo system (EHSS) is one of the most typical systems in the hydraulic system. The EHSS included a hydraulic actuator, a 4/3 proportional directional valve and a hydraulic power pack where the hydraulic pump is driven by an electric motor. During the operation, the flow rate in and out of the hydraulic actuator is controlled with one control signal to adjust the position of the spool in the proportional valve. With this characteristic of the proportional valve, a mechanical connection relationship between the inlet and outlet opening area is decided. Therefore, the EHSS has high robustness and easy to control[73, 74]. The construction machine operates with a variety of actuators and is supplied by the main pump. The flow rate and pressure in the system are changed greatly corresponding to the working conditions. Hence, the proportional directional valve causes energy loss at the outlet port, poor flexibility for overload, and generate the heat in the hydraulic system. In order to overcome the problems of the EHSS, one effective method is to break the mechanical linkage between the valve inlet and outlet. Then, the opening area of the inlet and outlet ports of the proportional valve can be separately controlled. The name of this system is called the independent metering (IM) system as shown in Fig. 1a. During the operation, the supplied flow rate from the pump to the hydraulic actuator is adjusted by the metering in the valve. Meanwhile, the output flow rate from the actuator can go directly to the tank through a maximum opening area of the metering out valve. The comparison between the EHSS and IM system is shown in Fig. 1b. The pressure loss in outlet orifice is reduced Then, the IM system can save energy consumption.

2.2 Proportional valve

In the IM system, the proportional directional valve is the key factor to decide the working performance and energy efficiency. The 4 ports 3 positions directional valve was used in the IM system. EATON company modified the structure of the IM system by using the 3 ports 3 positions direction valve. However, in recent time, the 2 ports 2 positions valve was normally integrated into the system due to their simple and flexible. The IM system uses four proportional cartridge-type valves that are operated independently to control the motion of a given hydraulic actuator. Eriksson et.al[78] developed a new Electro-Hydraulic Poppet Valves (EHPVs) along with the relevant control algorithms to realize this technology. Then, Patrick Opdenbosch[75] focused on the development of the control strategy with fault detection capabilities and its application to achieve intelligent electronic pressure control. The schematic of EHPV is shown in Fig. 2a with a solenoid operated bidirectional proportional valve and an internal pressure compensation mechanism designed to ensure a consistent minimum amount of flow initiation current.

Ju Ho Yoon et. al[79] proposed a new structure of the electric proportional pressure reducing valve (EPPR) valve in Fig. 2b which could change the pressure of the system. Based on the configuration of the EPPR valve, a mathematical model was built to simulate the valve by Haroon Ahmad Khan et.al[80]. However, the EPPR valve structure was very complexity and the mathematical model could not show the total characteristics of the valve. Therefore, the EPPR valve was designed by specialized drawing software. Then, a



(a) (c)

Fig. 2 (a). Schematic diagram of the electro-hydraulic poppet valve[75]. (b). Spool in the EPPR valve[76]. (c). Stepped rotary flow control valve[77].

flow force characteristic analysis using CFD S/W (Ansys Fluent) was conducted to verify the flow through the valve. To optimize the design parameters which have primary effects on the attraction force uniformity and the average attraction force, The finite element analysis and a neural network model were used to find the optimal parameter values.

K. Abuowda et. al[77] investigated the driving techniques for a novel stepped rotary flow control valve which has been developed for a hydraulic IM system (shown in Fig. 2c). The main structure of this valve included a stepper motor connected to a rotary orifice. The PWM electric control signal was sent to the coil of the valve via the H bridge and produced the electromagnetic force in the stators. The flow rate was adjusted according to the orifice opening area controlled by the rotation speed of the stepper motor. The multi-step response analysis of the valve has been investigated through a real test bench. The results showed that the micro-stepping driving technique reduced the friction ripples and could be used in different signal frequencies.

Based on the characteristic of each valve integrated into the IM system, we can conclude that the EHPVs had low leakage and low manufacturing cost. However, the EHPVs was affected by the flow force. Hence, the EHPVs was low stable and low accuracy. The EPPR[80] valve had high accuracy and stable. But the manufacturing cost of this valve was high and complex. The stepped rotary valve could achieve high stability and accuracy. In addition, the manufacturing cost was medium. Therefore, this valve could be used in many applications in hydraulic machinery.

2.3 Advantage and disadvantage of conventional IM system.

According to the configuration of the conventional IM system, as shown in Fig. 1a, it could overcome the problem of the conventional EHSS with lower loss energy and power consumption. The inlet and outlet orifices could be controlled independently. With the combination of several valves, the energy efficiency of the system was increased by allowing individual paths or control modes to correspond to different operating conditions. During the operation of hydraulic machinery, the load force was unexpected variation. The IM system could avoid the cavitation phenomenon caused by the variant force.

Besides the advantages, the conventional IM system had some drawbacks that need to solve. By increasing the numbers of valves, the costs of the components were increased and required complex controllers to manipulate the system. The switching between working modes made a sudden change in the speed of hydraulic actuators. Due to these drawbacks, the researchers are continuing to develop novel configurations for the IM system. Thereby helping to improve the application of the IM system in construction machines. Conversion trend from spool valve traditional to the IMV system.

3. IMV operation mode

3.1 The operation mode (PE, PR, HSRE, LSRE, LSRR)

The conventional IMV circuit mainly includes two proportional directional valves which enable the decoupling of the mechanical connection of the two orifices compared to EHSS as shown in Fig. 3. By using two different valves at the inlet and outlet port of cylinder, the IM system should be controlled to suit each mode of operation. There are 5 main operation modes in the conventional IM system which are listed as follows:

1. Power Extension Mode (PE)
2. Power Retraction Mode (PR)
3. High Side Regeneration Extension Mode (HSRE)
4. Low Side Regeneration Extension Mode (LSRE)
5. Low Side Regeneration Retraction Mode (LSRR)

The first two modes, PE and PR, are conceptually the same as the operation of a cylinder driven by a conventional proportional directional control valve. But these modes have a benefit of independent metering which cannot be attained by the directional control valve. During operations with powered load, the directional control valve causes energy loss due to the valve restriction in the return line. This drawback can be minimized by an independent metering concept.

In HSRE mode, the potential to save energy can be enhanced by recirculating the flow to the high-pressure side, which cannot be obtained by using the directional control valve. This indicated that the power extension mode has to use more power to lift the load during the operation while the velocity of the cylinder in the HSRE mode can achieve faster than the PE mode.

On the contrary, the other two modes, LSRE and LSRR recirculate the flow to the low-pressure side and then, save additional energy. The LSRE and LSRR modes can be used in the case of the external force and the velocity of the cylinder is the same direction. In the LSRE mode, the external force helps the cylinder extend and the flow rate at the bore chamber of the

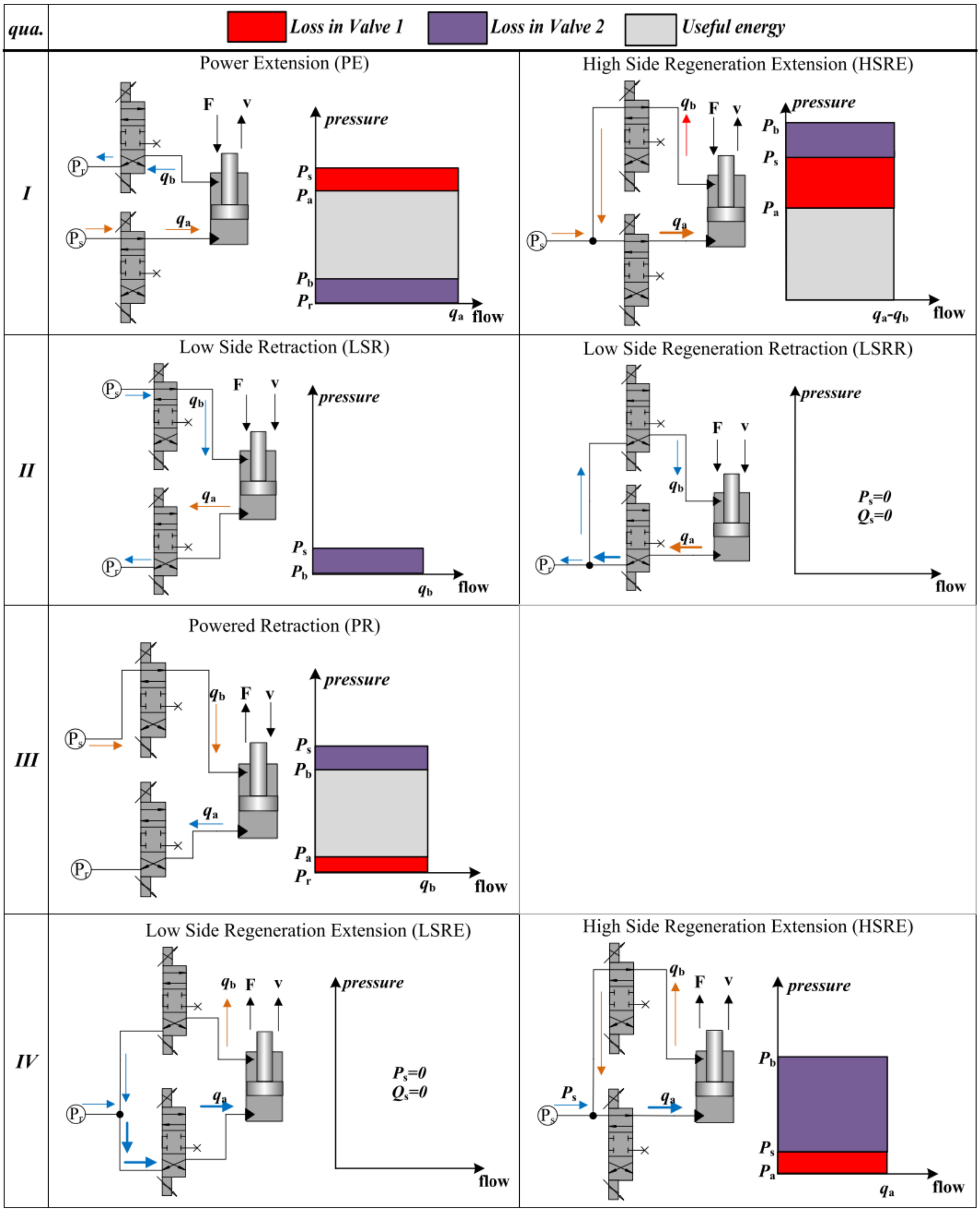


Fig. 3 Operating modes of conventional IMV systems[73].

cylinder can automatically be supplied by the flow from the tank and the rod chamber through two proportional directional valves. The LSRR can be used during the moving down process of the cylinder. The cylinder can move down without the flow rate from the pump by helping from the gravitational force. Because of the different volumes between the two chambers, flow in the bore chamber is partly transferred to the rod chamber, and excess is discharged to the tank.

3.2 The switching mode

The switching mode is designed based on the load quadrants, which was defined by the four combinations of the axial direction of load force and cylinder speed as shown in Fig. 4. The switching mode is used to reduce the losses and increase the stability and smooth switching between several operation modes. Bing Xu et. al[81] proposed the switching mode improve energy efficiency. A coordinate level is added to incorporate the pump control into the valve control. By the coordinate control of the pump and valves, the meter-in valve opens maximally and the pressure losses across the valves can be minimized. Erriksson et. al[82] proposed a mode transition based on the control of inlet and outlet opening area of valves. Outlet port control used to control the speed, has two operation modes which are recuperation mode and a neutral mode. The changing mode is designed based on load and pump pressure. Otherwise, Liu S et. al[83] proposed a control strategy for the IM system based on the cylinder force, velocity, and reference force. A MIMO control method was designed to control the speed and pressure in the Modiciency approach. This technique allows continuous mode switching based on the designed modes[63]. In addition, the IM system could operate following the speed and pressure levels. R. Ding et. al[73] proposed a bumpless mode switch approach for the IM system, which contains the dynamic dwell-time and a bidirectional latent tracking loop. This method aimed at solving the unstable switch by turning the quick switch into a slow one so that the temporary instabilities disappear for a long enough time. A boundary value solution of dwell time using multi-Lyapunov function was designed which can guarantee the stable of switch instant and reducing the effect of dwell time on the system response at the same time. An extension is designed to make the latent tracking design also suitable to the bidirectional mode switch in the independent metering system. The comparison results show that instability during instantaneous switching is eliminated and that the change in cylinder speed between the two modes is smoother[36, 37, 60, 84-86].

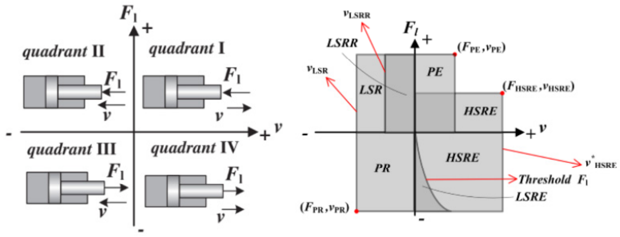


Fig. 4 Switching mode of the IM system[81].

4. Configuration and control strategy

Today, with the development of technology, many types of research on IMV systems are increasingly interested. With the goal of optimizing control and optimizing the cost of the system. Thereby, the IMV system has developed dramatically. From the original IM system that used five proportional valves, it has been reduced to using just one proportional valve. The studies not only focus on reducing the number of valves in the IMV system, but also towards stable control, energy-saving, and high accuracy of the system. Numerous studies have suggested optimal control strategies to ensure position and velocity accuracy. In this chapter, we will present the configuration and control strategy of the study. In this chapter, we will present the structure and control strategy of studies on IMV systems. Studies will be classified based on the number of proportional valves used in the IMV system.

4.1 Programmable Valve (5 Proportional valve)

The programmable valve configuration takes the advantage of four proportional valve configurations and adds the fifth proportional valve to enable a true cross port flow that is fully controllable (shown in Fig. 5). With this configuration, not only the circuit can be fully independently controlled for following the desired

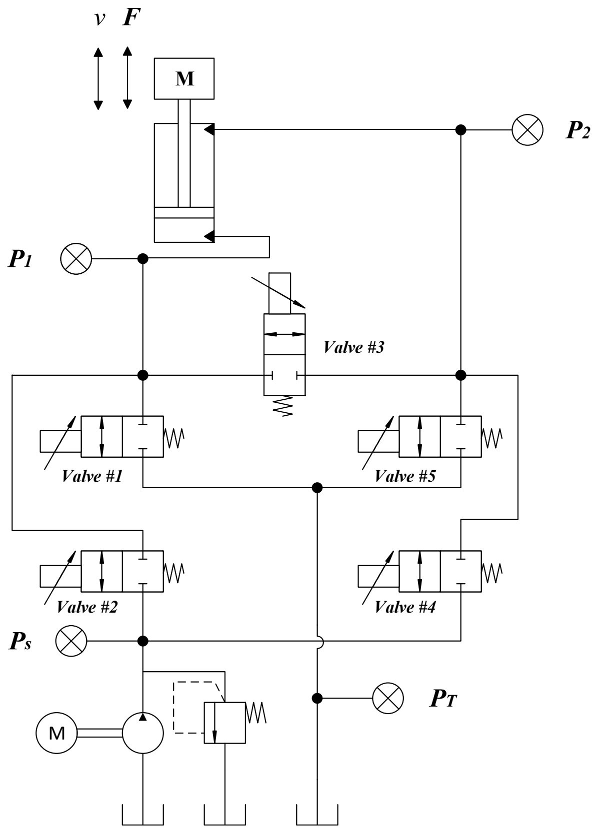


Fig. 5 The Programmable Valve configuration

trajectory and for keeping pressures at suitable levels to save energy at a certain amount, but also the cross port regenerative flow can be precisely controlled to keep the total pump (or active) flow energy usage minimum for maximum energy savings[40, 68, 83, 87, 88]. This configuration is developed by Bin Yao and coworkers[46, 83, 88]. In this study, the programmable valve configuration is combined with a pressure controller and adaptive robust controller reducing pump energy usage while achieving a good trajectory. In addition, two-level coordinated control is developed for this configuration, the task-level configures the valve usage for maximal energy saving and the valve-level utilizes adaptive robust control (ARC) technique to guarantee the closed-loop system stability and performance under various model uncertainties and disturbances[88]. Liu et al. has used this configuration and the appropriate components to realize the load sensing systems with both the meter-in and meter-out pressure compensation methods. With three distinct load sensing systems: the meter-in pressure compensation system (MIPCS), meter-out pressure compensation system (MOPCS), and pressure compensation load sensing system (PCLSS) are introduced and analyzed their effect on energy saving efficiency[40]. Kolks et al. have studied based on this configuration to switching between different operating modes to be achieved a smooth mode switching algorithm that minimizes losses and allows good motion trajectory[62, 63]. Three main operating modes are studied including: low pressure regeneration, high pressure regeneration and reverse mode. Depending on the mode there are different operating states based on the conditions of the load and the direction of operation. From the results of these studies have shown the efficiency of configuration programmable valves with lower energy consumption than conventional valves. However, the configuration of the programmable valve uses five proportional valves to difficulty in controls (especially in switching modes in the cycle) and the cost of the system was pushed up.

4.2 Conventional IMV (4 Proportional valve)

The conventional IVM (CIMV) circuit mainly includes four proportional valves (2/2 valve) and one check valve (shown as Fig. 6). By using the typical independent metering concept, this four-valve configuration with five distinct metering modes can drive the cylinder to the desired trajectories. It allows energy regeneration, an energy consumption reduction and subsequently, saves valuable energy[35, 37, 89-91]. This configuration has five modes, include: PE mode, PR mode, HSRE mode, LSRE mode and LSRR mode (introduce in chapter 3). With different input conditions, the system will selective the switching modes to operation follow the desired trajectories. Shenouda et al. have the analysis of the energy saving using independent metering configuration valve assembly is operating in a Pressure Compensated Load Sense control environment, this configuration saves energy even when used with a conventional Pressure Compensated Load Sense system but with the added capability of controlling back pressure[92].

In addition, in other studies about excavators, controlling the system according to the described trajectory is always considered and is the main goal of many studies. Tabor proposed to control the pressure in an actuator work port or minimize velocity errors due to valve coefficient errors. He makes new control algorithms using an equivalent valve coefficient. The embedded controller have been developed for both velocity control and supply pressure control. The velocity control and supply pressure requirements are optimized and have high efficiency[93, 94]. Shi et al. proposed the velocity and position combined control strategy based on the CIMV system and the pump-valve hybrid control principle. With this strategy, the actuators can operate follow the describe trajectory are smoothly and realize high-precision positioning, under the premise of the low energy consumption characteristics[47]. A control algorithm for the novel hydraulic driving system Micro-Independent Metering (MIM) using the stepped rotary valve has developed based on the configuration of the CIMV system. The algorithm measuring the required speed, the applied load and calculated flow. Then a suitable mode is selected and sends the control signal to the motor drivers. Then, the system can operational smoothness according to the work requirements[86].

Energy saving is also of the factors of interest in the studies. Choi et al. applied the IMV configuration in the excavators and compare the result with the conventional main control valve (MCV). The result achieved in both the boom-down (saving rate: 44%) and arm-down motions (saving rate: 21%)[37]. Two main factors to consider are throttling losses of valves and the energy consumption of the pump. To reduce the throttling losses, the valves should be opened maximum and just control the important valves. In addition, the combination of valve control and pump control are also researched methods for saving energy in excavators[42, 60, 95]. However, use the check valve causes power loss. Besides, controlling these four valves to obtain optimal performance is also difficult due to the increase of nonlinearities of the hydraulic system. Energy saving is lower than expected because of the direct connection between recirculating flow and supply flow as a result pressure difference is low. Finally, the use of four proportional valves increases the system cost.

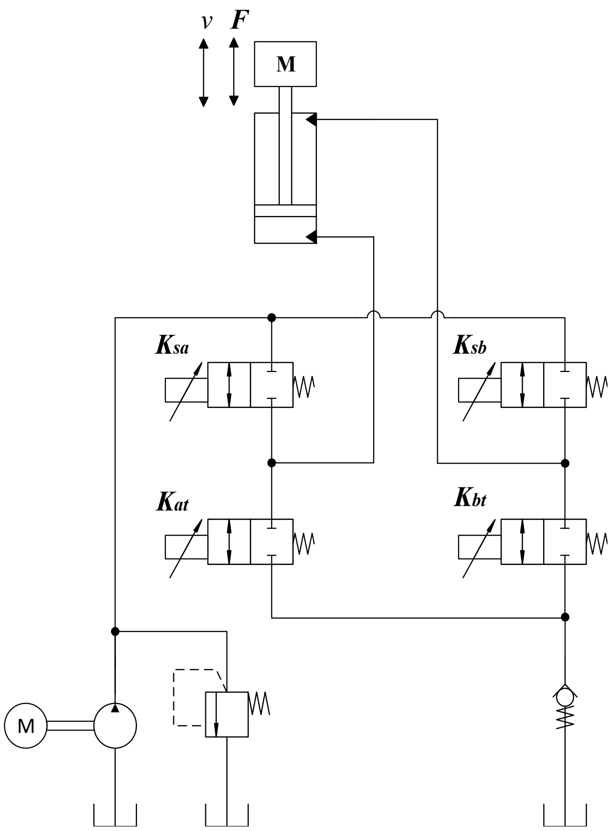


Fig. 6 The conventional independent metering valve

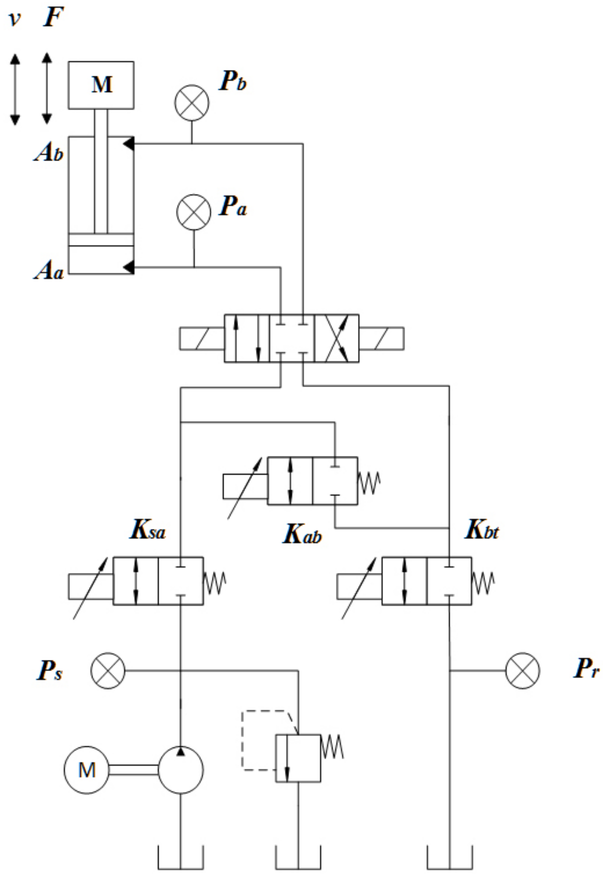


Fig. 7 The new configuration independent metering valve

4.3 New configuration IMV (3 Proportional valve)

A new and novel generation of an independent metering hydraulic circuit is proposed by Professor Ahn group[96]. The new configuration IMV system use three proportional valve and one directional valve to control the cylinder (shown in Fig. 7). Although, the NIMV configuration uses less proportional valves than the CIMV configuration, the modes operation of the NIMV are the same as CIMV mode. The three proportional valves can be operated proportionally by controlling the orifice gain. The orifice gain is calculated based on the differential pressure between the pump and cylinder chamber, the cylinder chamber and the tank. The control algorithms using an equivalent valve coefficient based on the research of Tabor[93]. Then, the control signal is transferred to the valve and operates according to the calculated modes. The directional valve is operated on the left side or the right side based on the mode operating. The energy saving is analyzed and compared with the CIMV. The result of NIMV configuration has achieved the energy saving better than CIMV configuration and can operate smooth follow the describe trajectory. However, the combination of the switching modes in the cycle has not been mentioned and the number of proportional valves is still many. Those are the limitations of this configuration.

4.4 Meter-in, meter-out (2 Proportional valve)

In this configuration, the hydraulic cylinder is controlled by two proportional direction valves (3/3) with the meter-in and meter-out orifices (shown in the Fig. 8). Therefore, this configuration has an advantage for control the proportional valve and the number of valves uses in the system. Although only using 2 proportional valves, the system can operate smoothly in the four-quadrant operating area of a differential cylinder and follow the describe trajectory[9, 50, 81, 97, 98]. The strategy in this configuration is to open a maximum of one proportional valve and control the remaining valve, so the throttling losses across the valves can be minimized. Xu et al. has proposed the coordinate control of pump and valves briefly couples electronic load sensing (ELS) included three levels (upper level- mode switch, lower level- valve/pump control, and coordinate control). The control signals will be transferred to the valves, in which one of the valves will be open fully and the other the valve will be controlled. The energy efficiency is improved and the system operates follow the desired motion trajectory[81]. Ding et al. used this configuration to designs a hybrid control method combining dynamic pressure-feedback and active damping control and can apply to a mini-excavator. This research reduces the strong vibrations of the independent metering system for mobile applications and guaranteed the optimal damping can be accurately captured under a considerable variation of operating conditions [72]. Shi et al. proposed the control strategy combined the velocity and position based on mode switching to control the boom and arm of the hydraulic excavator. The valve 1 open fully and the valve 2 is under the velocity feed-forward and position feedback (VFPB) method and the pump swivel angle is under the flow control method. With this strategy, the system can operate smoothly and high-precision positioning under the premise of low energy consumption[47]. However, the multiple operating modes and mode switching make it difficult to control the system. Therefore, the controller is designed with two

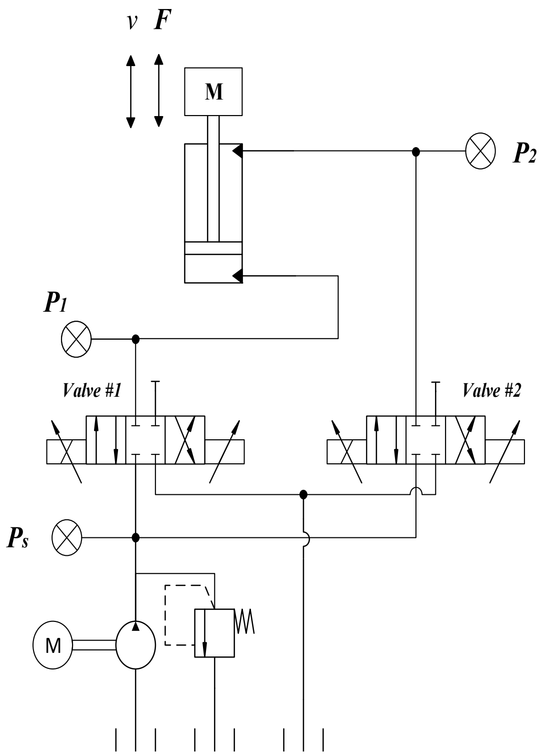


Fig. 8 The meter-in, meter-out configuration.

modes-velocity control and position control-based on the difference between the target and real displacements are proposed by X. Zhang. The results of this research can operate smoothly follow the target position and accurately by simply focusing on the control trajectory in the interface rather than depend on visual observation [58]. Although two proportional valves are used in this configuration, only one valve is controlled, the other valve is opened fully. Therefore, removed this valve will significantly reduce costs for the IMV system.

4.5 Meter-out control

Due to the high cost of proportionally controlled valves, reducing the number of proportional valves is necessary. Therefore, the configuration uses one proportional valve for IMV system is proposed by Ding, only one proportional valve and three switching valves are required in this setup[34] as shown in Fig. 9. In this configuration, a novel energy management algorithm that combines meter-out (MO) valve control with pressure/flow hybrid pump control is developed. With a single-edge, meter-out control valve is used, the system ensures operate smoothly in the four-quadrant

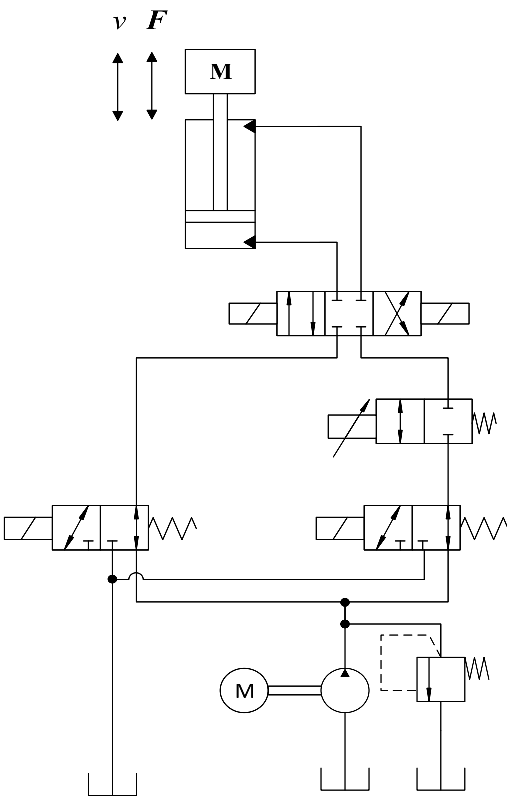


Fig. 9 The meter-out configuration

and the energy savings rate for a complete action cycle can reach 28% compared with a load-sensing system. The energy efficiency controllability is taken full advantage by control a single-edge and meter-out. The most significant feature of this system is the multiple control modes for each level as shown in Fig. 10. Each level will select the most efficient operating modes in terms to control follow the describe trajectory and controls the transitions between modes. The valves will be controlled according to the selected modes and enable significant energy savings without losing hydraulic circuit controllability for precise motion tracking (shown in Fig. 11).

4.6 Configuration with the accumulator

For energy saving, the "flow regeneration" technology is used in the IMV system to recycle the flow from one chamber of the cylinder to another when the cylinder is moving. In the excavator, the motion of the boom cylinder moves down can regeneration the energy and the motion move up of the boom cylinder is almost consuming a lot the energy consumption. Therefore, the solution to solve this problem is to use the accumulator. Lu et al. is used the programmable valve configuration and one diaphragm-type accumulator. The accumulator will store the flow when the piston of the cylinder moves downward and using such amount of flow to pump the piston up, so the energy recovery can be achieved[84]. In addition, the CIMV configuration combines with the accumulator is studied by Lyu. In this research, the accumulator is the power source of the independent metering part, guarantees the position tracking precision of the system and only uses about a half of the total energy[60]. Therefore, the IMV system combine with the accumulator has great potential energy saving for the excavator system and the premise for new research in the future.

5. Independent metering valve challenges

There are many limitations that prevent the IMV systems from application to excavators. In general, these challenges can be classified as follows:

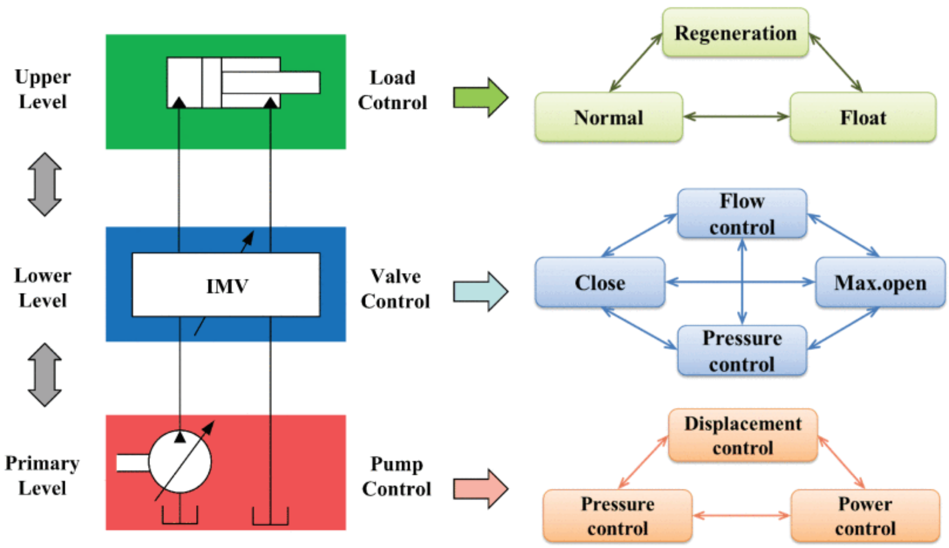


Fig. 10 Energy management architecture[34)]

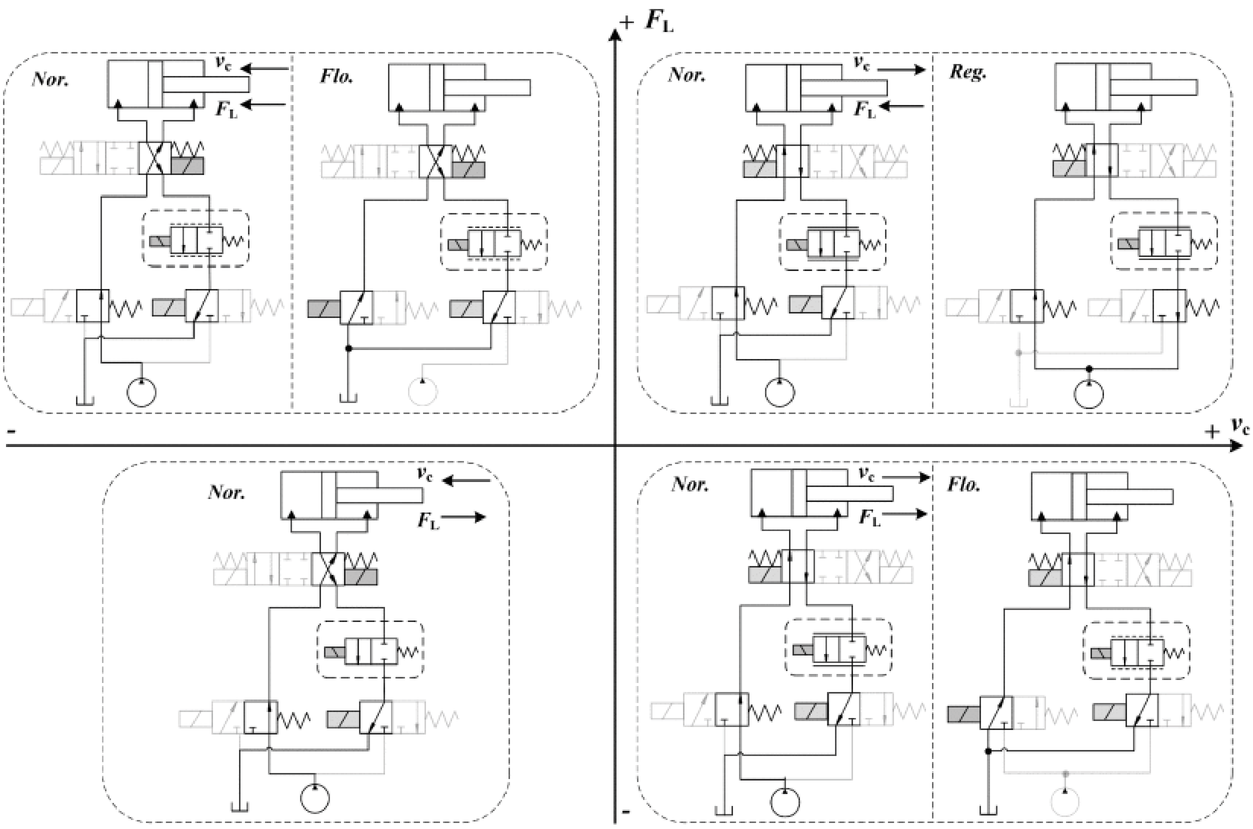


Fig. 11 Operating modes covering four load quadrants[34)].

Mode switching: The IMV control algorithm relies on a rule-based transition between many operating modes. The choice of operating modes depends on the load force effect on the system. In practice, the excavator will be under variable load. Therefore, the operating mode is affected and makes it difficult to control.

Cost: The proportional valves have a high cost than the direction valve. On the other hand, conventional excavators use the control signal from the joystick and transfer directly to the valve. However, with the IMV system, the control signals are routed to the controller, thereby calculating trajectories, and transferring control signals to proportional valves. Therefore, in addition to the high cost with proportional valves, the IMV system also incurs many other costs such as the controller, sensor...

Control: With each configuration of the IMV system, there will be different control methods and different operation modes switch. The valve/pump coordinate is controlled two parts at the same time causes certain control difficulties. Furthermore, pipeline losses and environmental influences also affect control values on the IMV system. Therefore, the stable control of IMV system is one of the important challenges that the researchers aims to achieve.

Oscillation: The hydraulic oscillation of IMV system is an important point to attend. The IMV reduces energy losses by control the orifices of the proportional valve, but this dwindles the controllability and produces velocity oscillation due to lack of damping at the enlarged orifices. Also, the mode switching operation with different dynamic characteristics creates the source of oscillation.

6. Conclusion

This paper introduced a comprehensive review of the independent metering valve system. The system could reduce energy consumption, operate smoothly follow the describe trajectory, and have important applications in the hydraulic excavators. The IMV circuit was made up of the proportional valves together. With different control modes, the hydraulic cylinder could operate according to the setting operation modes. The IMV configurations were reviewed, with each configuration having a different number of the proportional valves used. It could be mentioned that the conventional IMV configuration uses four-proportional valves with five operating modes such as: PE, PR, HSRE, LSRE and LSRR mode. In there, the LSRR mode was considered the most energy saving. And many control algorithms were developed for each different IMV configuration to reduce the energy consumption in the system. The challenges faced by the IMV system have been highlighted. The analysis of these challenges indicated that this system has been still limited in the application to practice and required multi-disciplines development techniques that rely on integrating different sciences ranging from electronics, mechanics, software, and artificial intelligence. Finally, all the developments and iterations are concerning on improving the control methods and efficiency of the system rather than improving the valve, the main factor influencing the outcome of the system. So, the future trend can apply the novel system that allows implementing intelligent control algorithms, or new proportional valve configuration will lead to new and novel technologies in this field.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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