Bu bir MMO yayınıdır

# EFFICIENT REGENERATION

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## ABSTRACT

The majority of industrial motion is linear motion, either provided by electromechanical drives or hydraulic differential cylinders, depending on the force density required. This paper deals with the intelligent integration of system's functionality into hydraulic directional control valves to make them competitive to or even better than electromechanical drives with regards to controllability and energy consumption. Contrasting arrangements of regenerative circuits are discussed and energy saving potentials are described.

## NOMENCLATURE

| | |
|---|---|
| Q | flow |
| p | pressure |
| $\Delta p$ | pressure drop |
| A | area |
| $\rho$ | fluid density |
| P, A, B, T | operating ports |
| $\alpha Z$ | cylinder area ratio |
| $\alpha$ | flow coefficient |

## INTRODUCTION

"Hydraulic cylinders are difficult to control" or "Hydraulic linear positioning is less accurate to that of electromechanical linear positioning". These are statements often heard in discussions regarding linear motion as used in industrial machinery.

It is true that electromechanical drives, due to their symmetrical behavior, in respect of speed and force are easy to set up for the desired motion.

It is also true, that hydraulic linear drives can provide exactly the same performance combined with the added feature of higher power density.

This paper describes the state of the art of hydraulic linear motion control, shows the major problems and offers a solution to overcome these by using a new type of hydraulic valve. Using “hybrid” valves, hydraulic differential cylinders become as symmetrical as electromechanical solutions in terms of controllability, with the additional potential to provide significant energy savings compared to today’s standard solutions.

## 1 HYDRAULIC LINEAR MOTION

### 1.1 Cylinders

Several styles of hydraulic cylinders are available such as ram type, telescopic, double-rod or single-rod cylinders.

Due to its mechanical simplicity, the single-rod double acting differential cylinder is utilized in the majority of applications.

It consists of one single ended piston rod connected to a piston, providing two areas of operation, which are unequal. Therefore assuming constant pressure, the cylinder’s behavior is asymmetrical regarding the forces in extend or retract direction.

Assuming constant flow, it is asymmetrical regarding the speeds to extend or retract.
Its main design parameter is the area ratio;

$$\alpha_Z = \frac{Ap}{Ar} \tag{1}$$

with Ap the piston area and Ar the piston area minus the rod area, the so called ring area.

In general, the machine designer would choose the ratio best matched to the demands of the desired motion. Practically there are established standards available that always lead to compromises. Ratios of 2:1 or 4:3 are most commonly used.

### 1.2 Valves

To match the standard cylinders with 2:1 or 4:3 area ratios to the demands of the application, the

control valve becomes the adjustable part of the circuit.
Hydraulic linear drives are controlled by directional control valves as well as by cartridge valve circuits. This paper focuses on the directional control valves (DCVs) as used in the majority of applications.

A standard DCV for cylinder control offers four operation ports and includes a spool that provides three operation positions in order to connect the ports in different ways. The ports are:

P pump connection
A, B operating ports, connected to the cylinder
T Tank connection

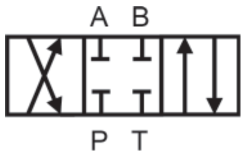
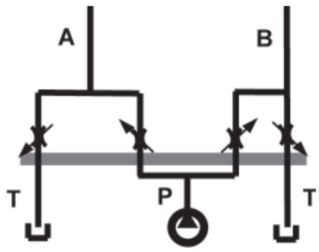



*Figure 1 shows* the symbol of such valve.
**Figure 1:** 4 connections / 3 positions DCV

The valve itself may include an area ratio similar to a cylinder.

I. e. the spool edges may be shaped in a way that they open up different areas to particular ports of the valve. Within this paper the areas inside the valve will be described in the form 1:1:1:1 sequencing the areas of the connections TA:AP:PB:BT. A "1" represents 100% of the area needed for nominal Q at nominal $\Delta p$ on the edge.

In Figure 2 a functional drawing is shown where the grey line symbolizes the interaction between the




four throttling edges. The same visualization is used in /Bac92/.
**Figure 2:** Functional drawing of spool areas

A standard DCV 1:1:1:1 generally is able to control every cylinder area ratio.

### 1.3 Hydraulic Drives

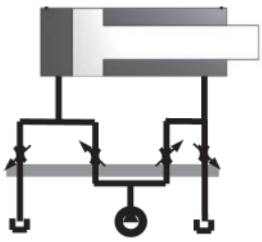
Combining a valve and a cylinder results in a hydraulic drive.
A hydraulic drive creates forces and provides speeds when extending as well as retracting. The maximum force independent of the direction can only be created when the cylinder is stopped. As soon as the cylinder is moving, the force is reduced by that portion of the supply pressure that is lost as pressure drop Δp at the throttling edge of the valve.

When moving an unloaded cylinder with maximum speed, nearly the complete supplied energy is converted to heat due to throttling losses in the valve. Therefore this type of linear motion control offers a huge potential to save energy.

## 2 HYDRAULIC DRIVE CIRCUITS

### 2.1 Standard Circuit

The most common circuit used for hydraulic linear motion in industrial applications is the differential



cylinder 2:1 in combination with a standard DCV 1:1:1:1 (Figure 4).

**Figure 4:** Standard Circuit

Using this combination of valve and cylinder, the conditions when extending with constant speed are as follows:

The valve will move to position PA-BT. Due to the cylinder area ratio 2:1, twice the amount of oil has to flow through PA compared to BT. As predefined; valve areas PA and BT are equal. Using the equations

$$Q_A = 2 * Q_B \quad (2)$$

$$Q = \alpha * A * \sqrt{\frac{2}{\rho} \Delta p} \quad (3)$$

leads to a pressure drop across PA 4 times higher than across BT. This results in asymmetrical pressures in A and B of the cylinder, creating asymmetrical forces. This is valid for either extension or retraction of the cylinder (Figure 5)

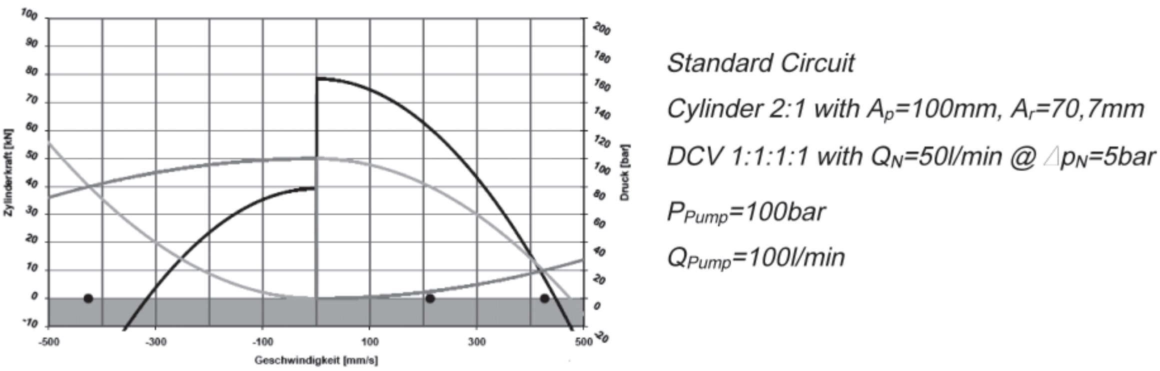



**Figure 5:** Relationship between pressures in A (green) and B (orange) and the cylinder force (black) over valve opening respectively cylinder speed

The example shows the results for a standard cylinder with 100mm bore diameter and 70mm rod diameter. System pressure is assumed to be 100bar, the valve is chosen to provide a nominal flow of 50l/min at 5 bar pressure drop across each edge. For the ease of comparison these values are kept constant for all following circuits.

Then maximum force for extension with 80kN is 200% compared to retraction force.

The blue points in the graph visualize the limits of the pump. The maximum flow is set to 100l/min. In retracting direction (left side of the graph) the pump could provide flow for speeds up to 420mm/s, but due to pressure drops inside the valve, the cylinder only can reach 320mm/s. At this point, all the energy is used up by losses inside the valve and no more force can be provided.

In extending direction (right side of the graph) there are two blue points visible. The first one at 210mm/s shows the flow limit for the standard circuit. The second one at 420 mm/s shows a theoretical point that could be reached using regenerative circuits. These will be explained later on.

## 2.2 Matched Valve

One solution to get rid of the asymmetrical behavior of the standard circuit described in 2.1 is to match the valves area ratio to the one of the cylinder. Using a 1:1:0,5:0,5 valve in combination with a 2:1 cylinder will result in the curves shown in Figure 6:

Comparison of figure 6 with figure 5 shows, that the matched combination of valve and cylinder provides the same asymmetrical forces but combined with symmetrical pressures in A and B, leading to equalized pressure drops across the valve edges PA-BT or PB-AT, subject to the direction of movement. Force resolution over stroke increases plus controllability of the cylinder also increases, as all spool edges (Flow areas) show symmetrical pressure drops.

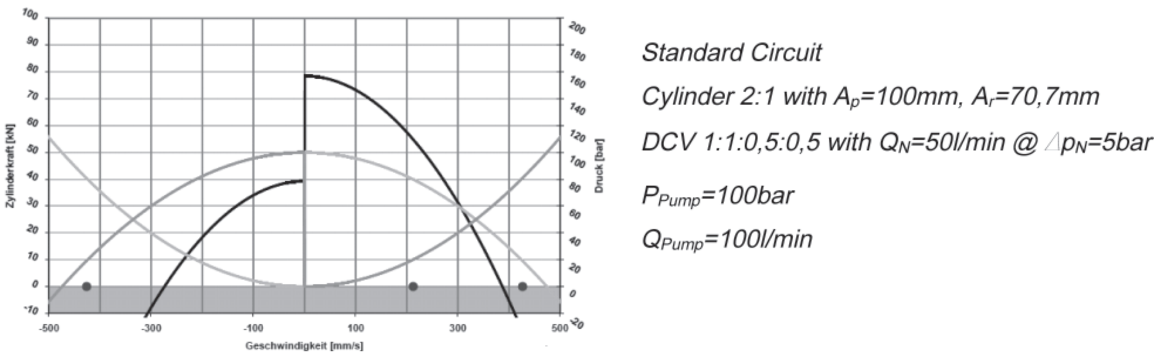


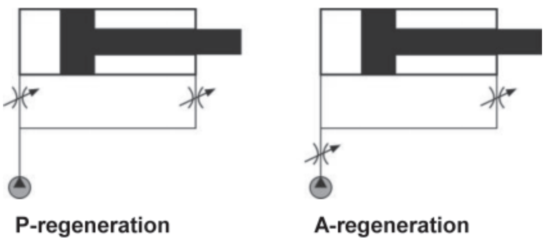

**Figure 6:** Matched valve and cylinder

Extension force is reduced due to balanced pressures. Retraction can only take place with reduced speed, as the force is consumed by losses already at 270mm/s.

### 2.3 Regeneration

The next step on the way to symmetry is the "regenerative" circuit. Regeneration means feeding oil from the rod side of the cylinder to its piston side. If the extension speed is assumed to be the same as with a standard circuit, feeding oil from B to A creates the opportunity to utilize a smaller pump size – with the accompanying cost reduction. As a consequence regeneration circuits are often called money-saving-circuits – but they can do even more.

There are two possible locations where the rod oil can be redirected to the piston side: In front of or




behind the PA flow area of the valves spool. We have named these two circuits according to the connection ports either P-regeneration or A-regeneration (figure 7).

**Figure 7:** P- and A-regeneration

#### 2.3.1 P-regeneration

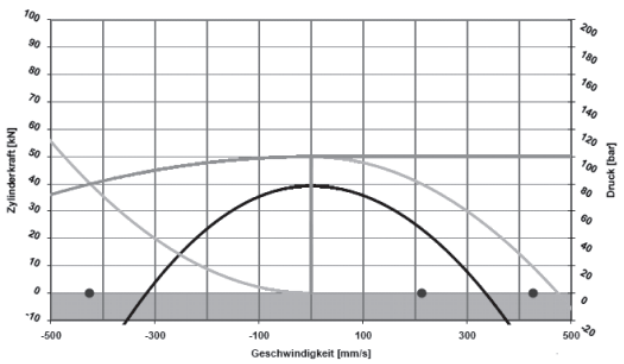
P-regeneration is the most commonly used money-saving-circuit. It can be realized in two different ways: External check valves can be used in combination with a standard DCV or a customised spool within the DCV simultaneously achieving a connection from B to P and P to A. Figure 8 shows the two options:

**Figure 8:** P-regeneration with external check valves or internally utilizing a customised spool design

Although the internal valve solution utilizing a customised spool appears to be more cost efficient when compared with the external check valve manifold option, it cannot be recommended.
As figures 9 and 10 show, both circuits provide symmetrical force behaviour.

To simulate the conditions of the external check valves, the B-T/A/P edge is set to 10 in the calculation of the external P-regeneration. The value of 10 simulates a 10 times larger area for the flow compared to the nominal maximum area inside the valve of 1. As check valves have very low pressure drop losses when they are open, this is a good approximation.

Due to the negligible pressure drop of the check valve the B-pressure during extension is equal to system pressure. The oil volume of the cylinder rod side is fed back to the P port and adds to the




*External P-regeneration Circuit*

*Cylinder 2:1 with $A_p$=100mm, $A_r$=70,7mm*

*DCV 1:1:1:10 with $Q_N$=50l/min @ $\Delta p_N$=5bar*

*$P_{Pump}$=100bar*

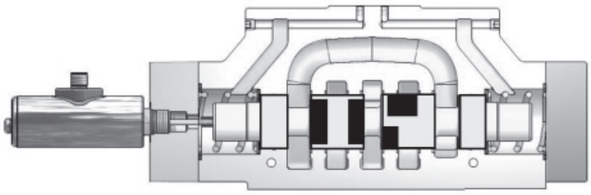
*$Q_{Pump}$=100l/min*

pump volume. Therefore the regeneration offers twice the speed value for extension when compared to the standard circuit.

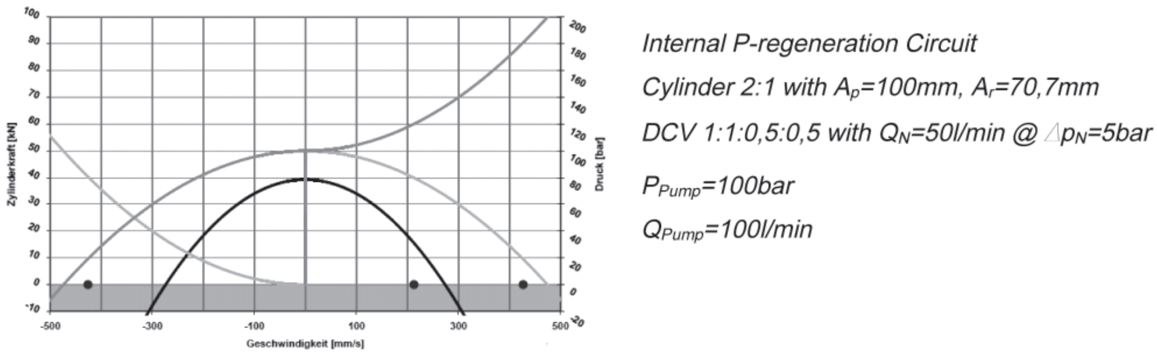
**Figure 9:** P-regeneration circuit realized with check valves

The far right blue point on the right hand side of the diagram represents the new speed limit. In figure 9 it cannot be achieved due to system pressure of 100bar which is too low. Compared to the standard circuit with 210mm/s max. extension speed, P-regeneration offers 50% more speed with above system parameters. As a result of the by passed control edge B-T, the controllability is degraded, exemplified by pulling loads (Over Running) which are difficult to control resulting in cavitation.

With regard to force and speed, the internal P-regeneration shows poorer results, especially the pressure in B increases above system pressure even at very low speeds. The reason for this is that the spool does not open to provide a full flow area of 1 in the connection P-B; it requires half of the



flow area for the B-T connection. In figure 10 you can see, that the integration of this connection




leads to smaller control areas on P-B and B-T compared to standard spools.

**Figure 10:** Spool design for internal P-regeneration

**Figure 11:** P-regeneration circuit achieved by the use of a customised spool option

The danger of overloading the cylinder increases. In a 2:1 cylinder system there is the potential to create twice the system pressure in B in the worst case. If the system pressure is higher than 175bar, cylinders may fail if steps are not taken to limit this potential to generate excessive pressure. Figure 11 shows the corresponding graphs.

### 2.3.2 A-regeneration

The concept of the A-regeneration is a result out of our analyses of the previously described circuits and their pros and cons. The major disadvantage of the external P-regeneration is the missing B-T flow area, which decreases the controllability of the cylinder. The internal P-regeneration problem is the pressure accumulation due to the B-P flow area. The oil from B has to flow to A. So the logical step is to avoid this flow path via the pump and to connect B with A by keeping the spool control flow area on the B-side. This simple step has a dramatic influence as shown Figure 12.

The PA flow area only sees half of the oil volume compared to the P-regeneration at the same speed. The pressure drop across PA therefore is significantly reduced and more force can be provided during extension.

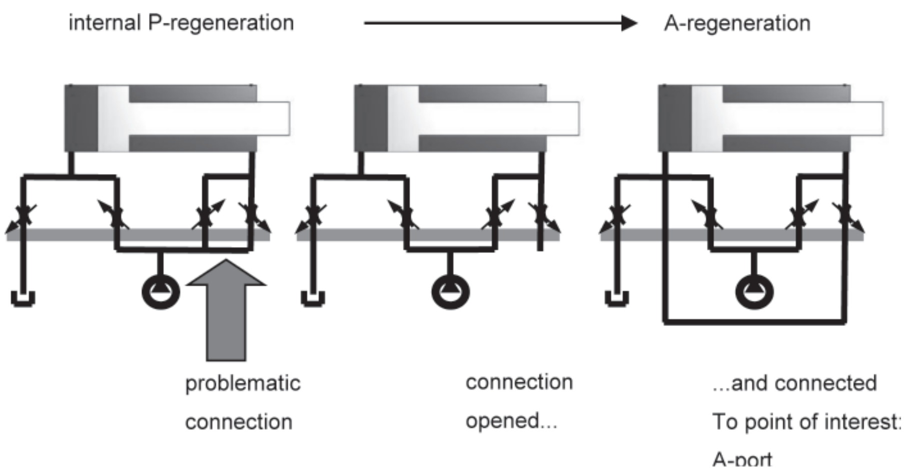
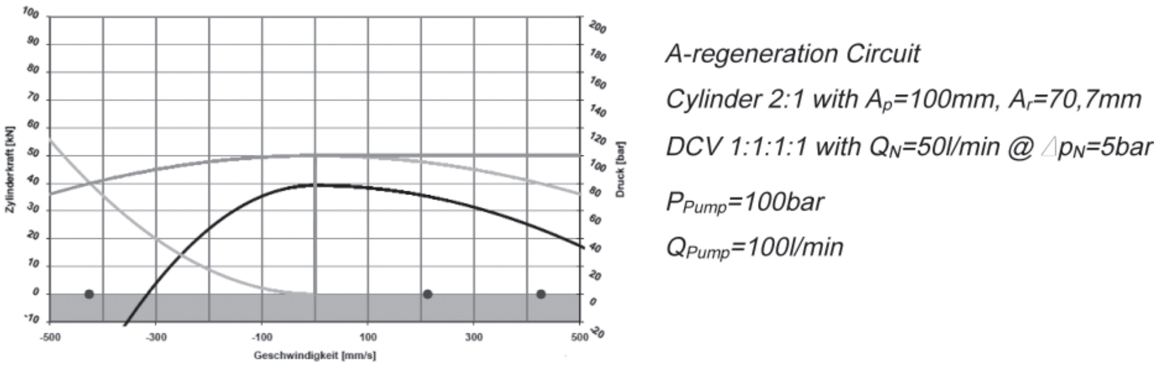



**Figure 12:** The way to A-regeneration

Figure 13 shows, that the cylinder now can reach speeds up to 420 mm/s and still offers a force of approximately 24kN at this point.




This leads to an increase of 200% in potential extension speed compared to that of a standard circuit combined with usable force over the complete speed range.

**Figure 13:** A-regeneration

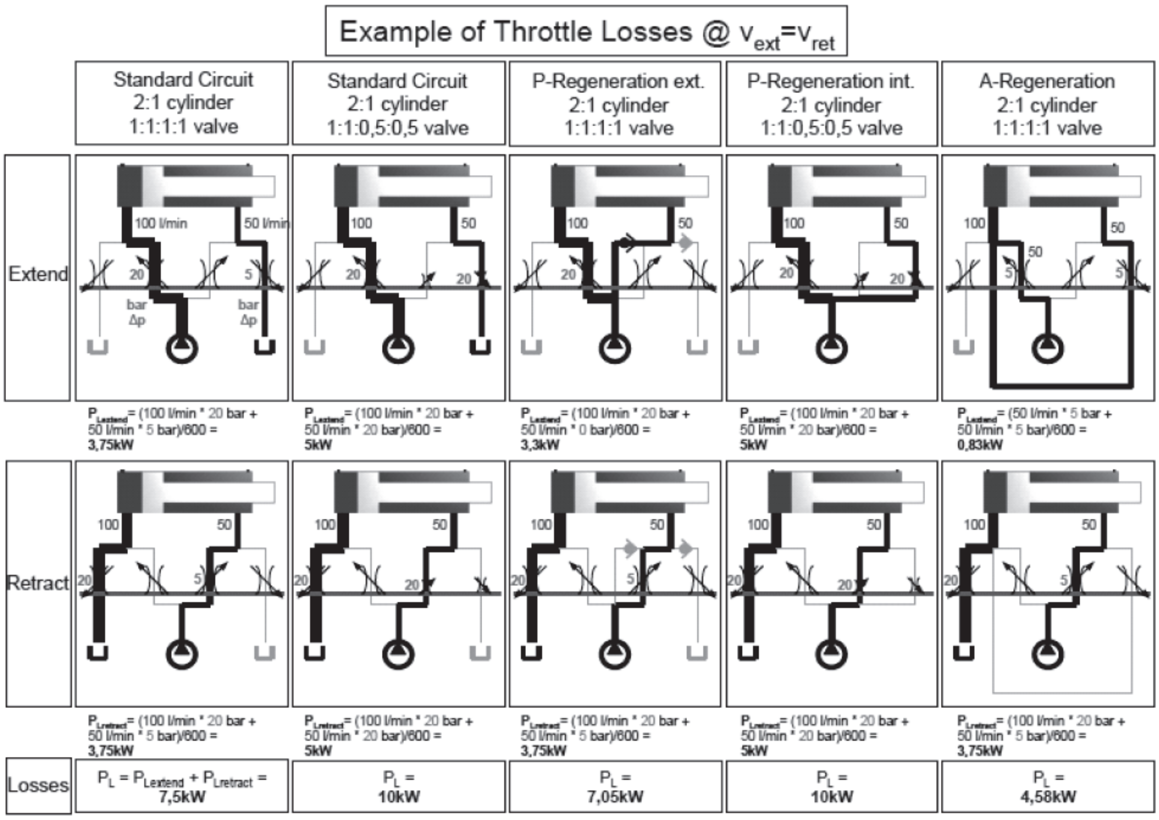
The maximum achievable force is only half of the standard circuit due to the higher pressure in the rod side of the cylinder caused by the return of oil to A. This remaining problem can be solved: Simply by the addition of one check and one on-off valve the A-regeneration can be converted to standard circuit whenever needed without the danger of becoming overloaded. The A-regeneration becomes the A-Hybrid.

## 3 EFFICIENCY

Each of above described circuits besides the new A-regeneration are used in industrial applications.

The application itself is the major driver to decide, which of the circuits is the right and the most efficient one.

A comparison of the energy losses of the different circuits caused by the throttling edges in the valve makes the decision easier. The matrix shown in Figure 14 shows all five discussed circuits, both well for extension and retraction. To compare the losses on the control areas of the valves, the cylinder




speeds for extension and retraction are assumed to be equal for all circuits. The force delivered by the cylinder is assumed to be 0N. The spool flow area of “1” equates to the values of 50l/min @ 5bar Δp.

**Figure 14:** Comparison of Efficiency

According to equation (3) twice the flow, respectively half throttling area on the valve’s control ports, creates four times the pressure drop. Looking at the overall throttle losses in the bottom line of Figure 14, it becomes obvious that the A-regeneration circuit offers an increased efficiency of more than 30%!

## CONCLUSION

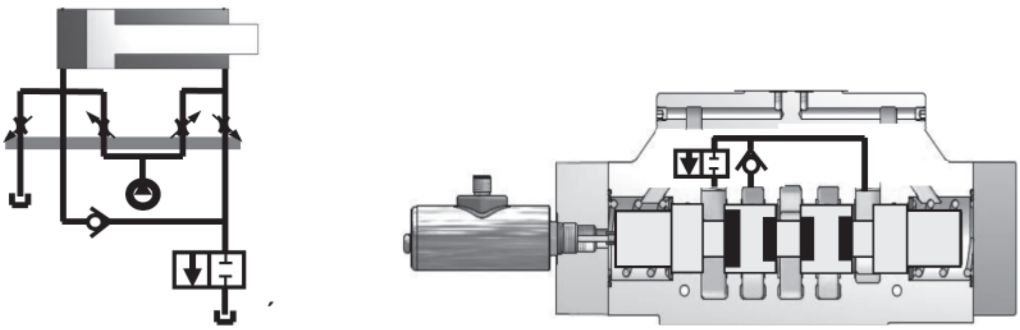
Subject to the demands of force over stroke and/or speed combined with force the system designer has to optimize cylinder area ratio and valve to achieve a perfect fit.

A machine needing to extend high loads and to retract lower loads should be equipped with a cylinder whose areas provide the same ratio of the required forces to move the loads. If speed is not a critical parameter, the standard circuit will do the task. Matching of spool area ratio to cylinder area ratio might lead to symmetrical pressure drops and better controllability in case of closed loop movements. Energy efficiency cannot be improved in this case.

If speed is a critical parameter of a define cycle time of the whole machine process, the appropriate modifications to the circuit have to be implemented.

The use of a P-regenerative circuit can improve extension speeds as previously shown but at the cost of reduced extension forces.

The ideal solution, for say the clamping mechanism utilized in moulding machines, is a combination of high speed with low forces to open and close the mould, switch able to low speed and high forces to clamp the mould. Today's circuits either use oversized valves and or cylinders in order to reach the desired performance of speed combined with force. It should be noted that speed and force are not required in the same time frame and therefore today's solutions waste significant levels of energy.
The perfect fit for clamping units and many other applications is an A-regeneration circuit for fast, energy saving movements combined with a standard circuit to create high forces when needed. This is called the A-Hybrid.



The A-Hybrid circuit consists of a DCV with integrated on/off and check valve housed within a standard valve body. The circuit is explained in figure 15.

**Figure 15:** A-Hybrid circuit and assembly

This type of valves will allow machines to providing shorter cycle times with reduced energy requirements.

A-regeneration and A-Hybrid valves provide efficient regeneration.

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