Proportional Valves Component Technology

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1 Proportional Solenoids

Proportional solenoids represent the linking element between electronics and hydraulics. The proportional solenoids are a form of DC linear solenoids. Proportional to the electrical current as the input variable, they produce force and travel as the output variable.

Corresponding to the practical application, a differentiation is made between:

- solenoids with comparatively linear stroke/current relationship over a reasonably long stroke length, the so-called "stroke-controlled solenoids"
  and
- solenoids with particularly defined force/current relationship over a very short stroke, the so-called "force-controlled solenoids".

Only DC linear solenoids can be used for the current-proportional change in the output variables force and stroke. Due to their stroke-dependent current consumption, AC solenoids must assume their final stroke position as soon as possible.

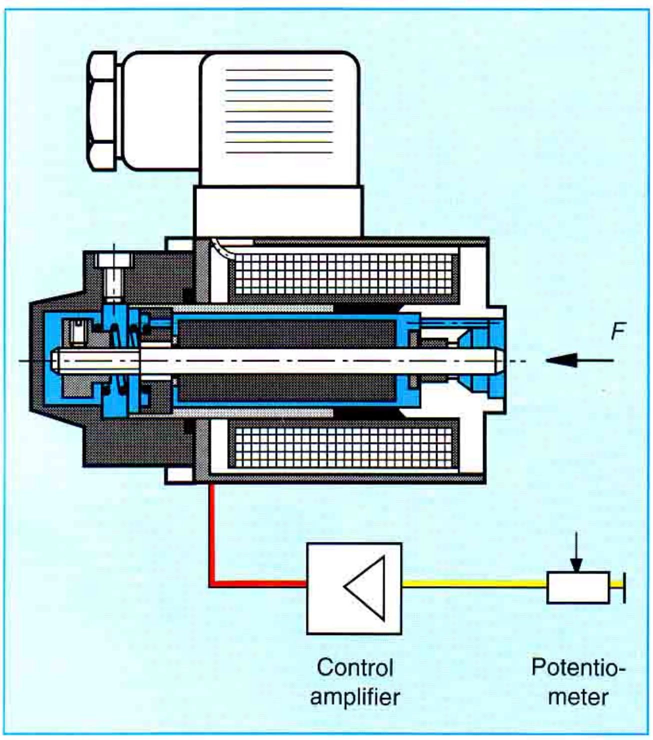


Fig. 9: *Force-controlled proportional solenoid*

1.1 Force-controlled Solenoid

The solenoid force is controlled by the change in current I in the force-controlled solenoid without the armature of the solenoid performing a measurable stroke.

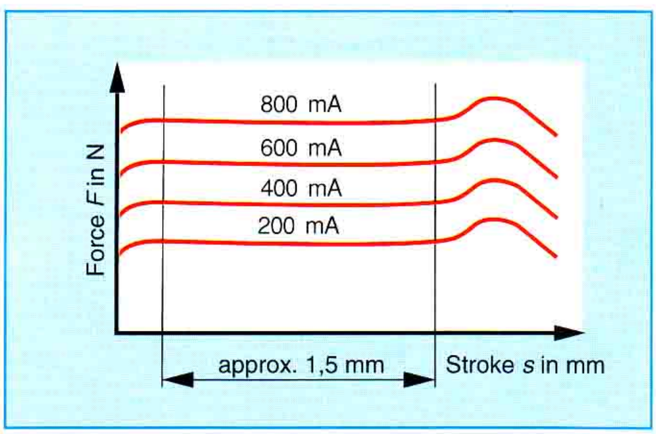
Due to current feedback in the electrical amplifier, the solenoid current and therefore the solenoid force are kept constant even if resistance changes.

The main feature of the force-controlled proportional solenoids is the characteristic force-stroke curve.

The solenoid force remains constant over a defined stroke range at constant current.

The stroke for the solenoid shown in this example is approx. 1.5 mm. The solenoid is used in this range.

The force-controlled solenoid is of compact design due to the short stroke. In view of this short stroke, the force-controlled solenoid is used particularly for pilot-operated proportional directional and pressure control valves with the solenoid force being converted into hydraulic force. The proportional solenoid is a controllable "wet pin" DC linear solenoid contained in an oil bath.



Diag. 1: *Characteristic force-stroke curve of force controlled solenoid*

1.2 Stroke-Controlled Solenoid

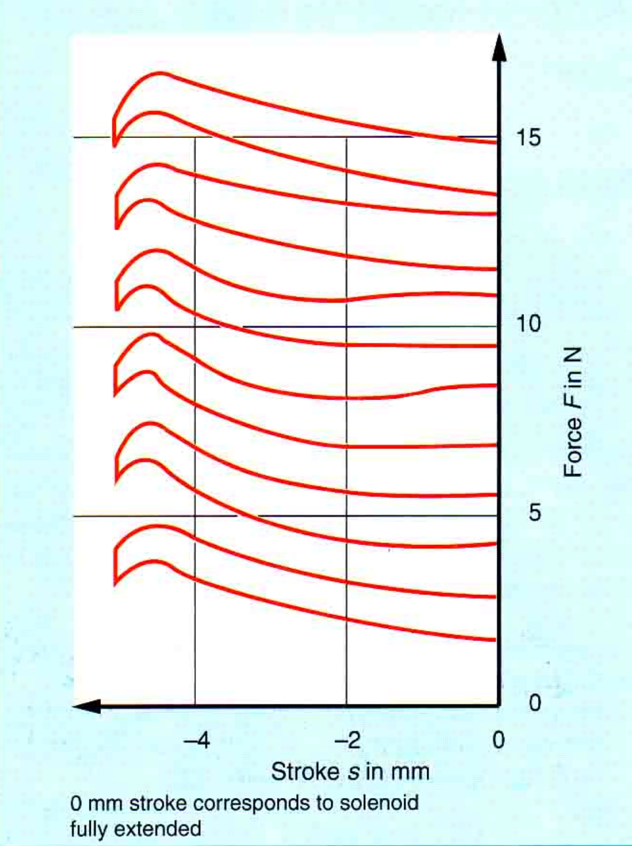
In the case of the stroke-controlled solenoid *(Fig. 10)*, the position of the armature is controlled by a closed-loop control circuit and maintained irrespective of the counter-pressure, provided it is within the rated working range of the solenoid.

With the stroke-controlled solenoid, the spools of proportional directional, flow as well as pressure control valves can be directly operated, and be controlled in any stroke position. The stroke of the solenoid is between 3 and 5 mm depending on the size.

As already mentioned, the stroke-controlled solenoid is primarily used for directly operated 4-way proportional valves.

In conjunction with the electrical feedback, the hysteresis and the repetition error of the solenoid are maintained with very tight tolerances. In addition, any flow forces, which occur at the valve spool are compensated for (relatively small solenoid force in relation to the interfering forces).

In the case of pilot operated valves, the controlled hydraulic pressure is applied to a relatively large control area. The available positioning forces are therefore considerably greater and the percentage effect of interfering forces is not so marked. For this reason, pilot operated proportional valves can be implemented without electrical feedback.



Diag 2: *Characteristic curve, stroke-controlled solenoid*

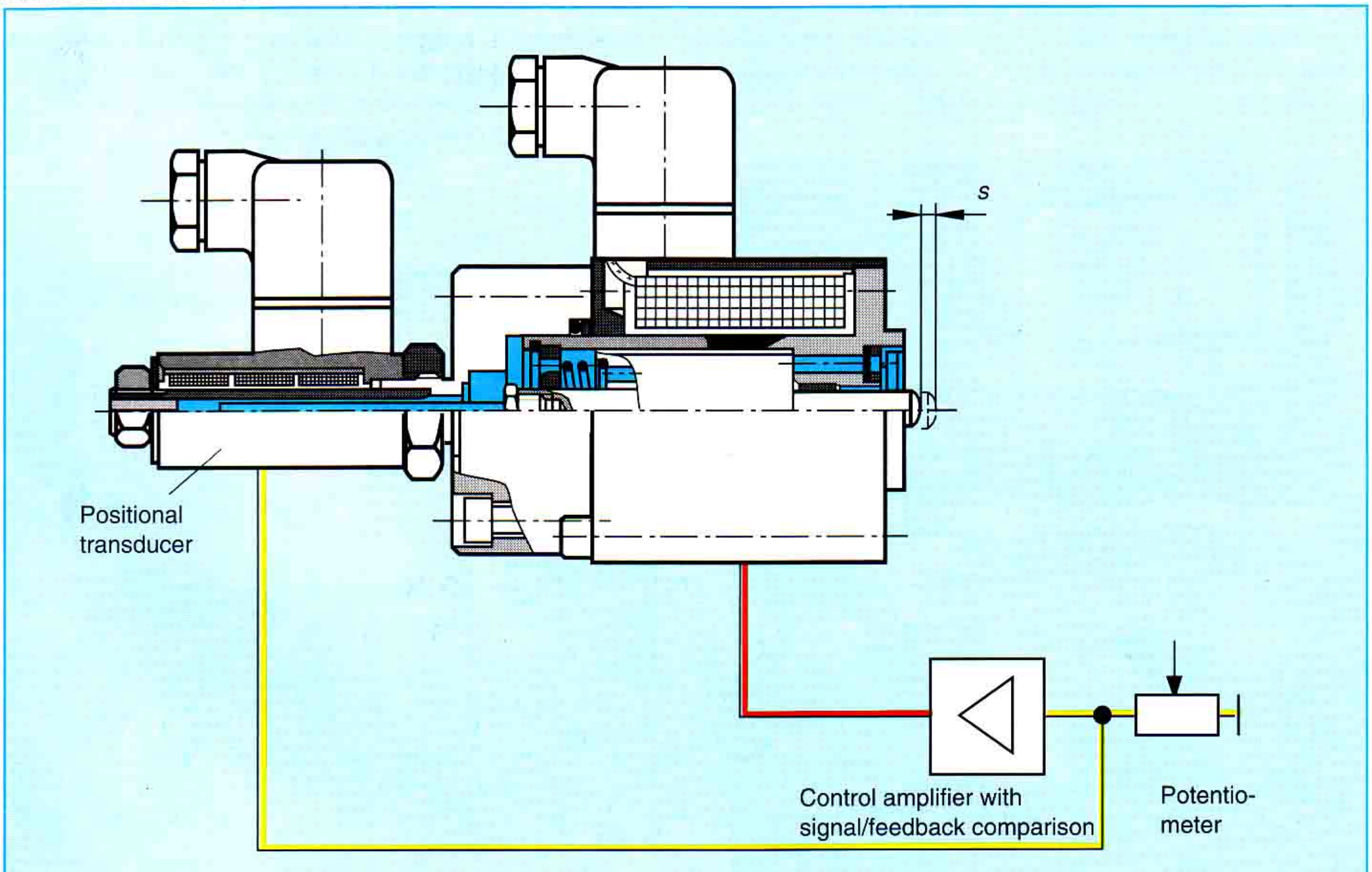


Fig. 10: *Stroke-controlled proportional solenoid*

2 Proportional Directional Valves

A proportional directional valve is used to control the direction and amount of a flow.

2.1 Directly Operated Proportional Directional Valve

In connection with this valve, the points applicable to the following proportional directional valves will also be discussed by way of example such as hysteresis, repetition accuracy, control spool, basic principles for characteristic curves and the time characteristics of the control spool.

The proportional solenoid acts directly on the control spool in the same way as a conventional directional control valve.

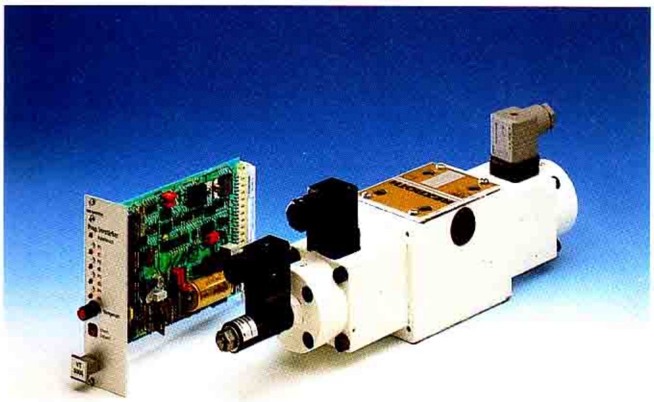


Fig. 11: *Directly operated proportional directional valve Type 4WRE 10 with electrical feedback, electronic control type VT5006*

2.1.1 Function

The basic components of the valve are the housing (1), one or two proportional solenoids (2) with analogue stroke-flow behaviour, as shown in *Fig. 12* with inductive positional transducer (3), the control spool(4), as well as one or two return springs.

The control spool (4) is held in the centre position by the return springs (5) when the solenoids are not energized. The control spool is operated directly via the proportional solenoid.

In the case of the spool shown in *figure 12*, the link between ports P, A, B and T is closed in this arrangement. The control spool is now shifted to the right when the solenoid A for instance (left) is energized, producing the connection between P - B and A - T. The higher the level of the signal coming from the electrical actuation system (refer to the chapter *"Electronic Control for Proportional Valves"* for detailed description) the further the control spool is shifted to the right. The stroke is therefore proportional to the electrical signal. The greater the stroke the greater the opening to flow and therefore the greater the flow. The left solenoid in *Fig. 12* is equipped with an inductive positional transducer to record the actual position of the control spool and to "indicate" to the electronic amplifier the position (in the form of an electrical signal (Volt) proportional to the stroke).

Since the positional transducer is a double stroke device, spool positions both sides of centre are monitored.

In addition, the transducer is of pressure-tight design, thereby rendering a leakage oil port and additional sealing facilities unnecessary. This means that additional coefficient of friction cannot adversely effect the accuracy of the valve.

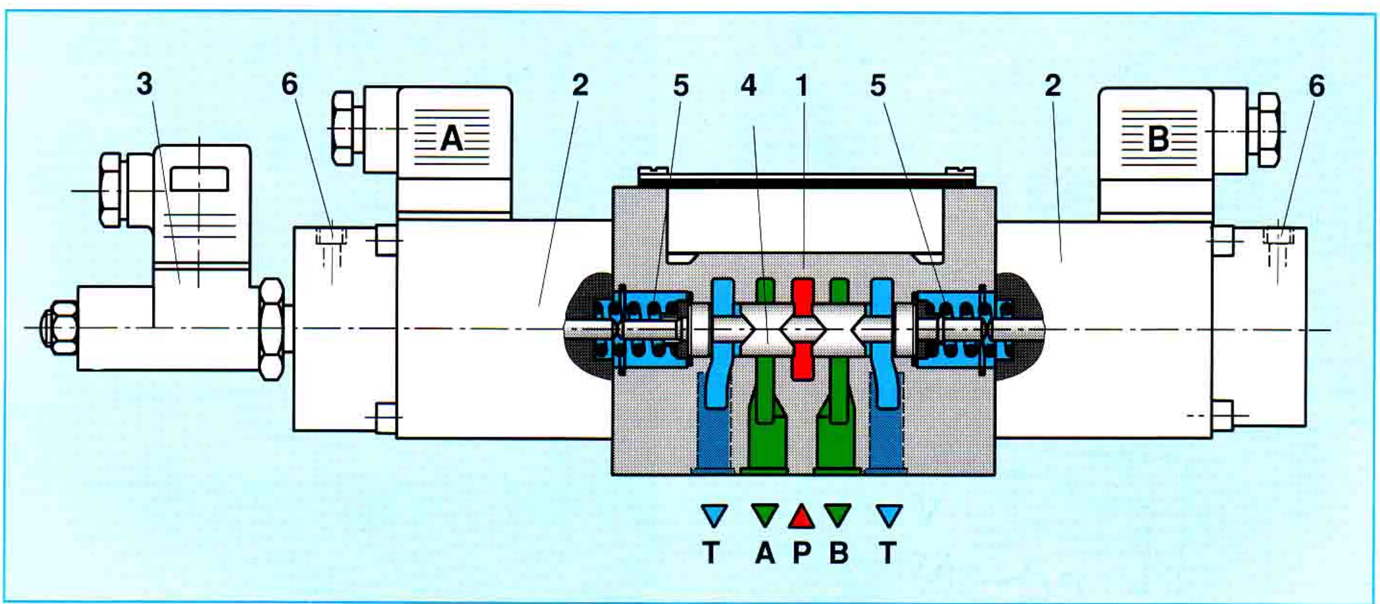


Fig. 12: *Directly operated proportional directional valve with electrical feedback*

In the electrical amplifier, the actual signal (actual position of the control spool) is compared with the specified value (command signal). This therefore represents a closed loop position control which detects any deviations between the specified value (command signal) and the actual signal and corrects the deviations by means of corresponding signals to the relevant solenoid.

In practical applications, this means that the hysteresis and the repetition accuracy of the valve are 1 % depending on the size of the valve.

2.1.2 Hysteresis

General: Dependency of a condition on previous conditions.

If the electrical signal is increased from 0 to max. and decreased once again, the spool assumes a certain position proportional to the signal. The resulting deviation at constant command signal, which however, is set in various directions (coming both from the minimum and the maximum value) is termed hysteresis or hysteresis error *(Diag 3)*.

2.1.3 Repetition-Accuracy
(also termed repeatability)

This term describes the range within which the output signals are obtained at repeated setting of the same input signal. For the control spool, this means that a deviation of 1 % with respect to the given position is achieved with repeated setting of the same command signal (for WRE).

The valve shown in *Fig. 13* has no positional transducer on the solenoid. The position of the spool is therefore not additionally monitored. Once again depending on the valve size, this arrangement results in a hysteresis of 5 – 6 % and repetition accuracy of 2 – 3 %.

This degree of accuracy is completely adequate for many applications so that this version represents a relatively inexpensive solution.

2.1.4 Control-Spool Version

As can be seen in the sectional view *(Fig. 12)*, the control spool differs from the spool in a normal directional control valve. It features triangular shaped orifice-like throttle openings, providing progressive flow characteristics *(Diag 4)*.

The control lands of the triangular notches *(Fig. 14)* and the control lands of the housing constantly remain engaged with respect to each other in all positions of the spool. This means a constantly defined opening to flow in the form of a triangle.

There is therefore no position as in the case of standard directional control valves, in which these two control lands only open after an "idle stroke", and then re-engage on closing.

In addition the inlet and outlet are always throttled.

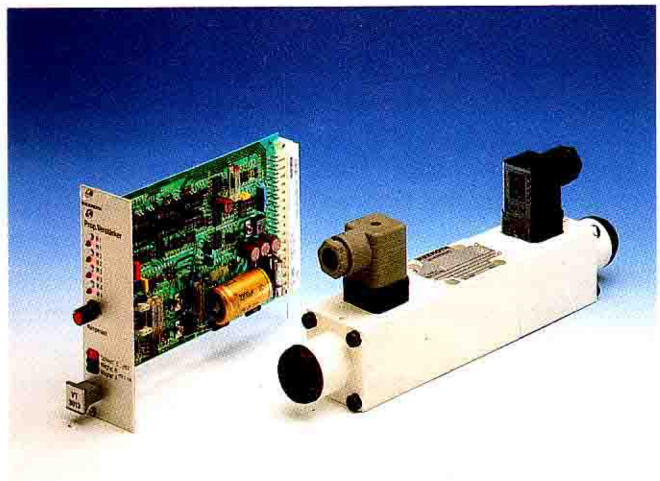
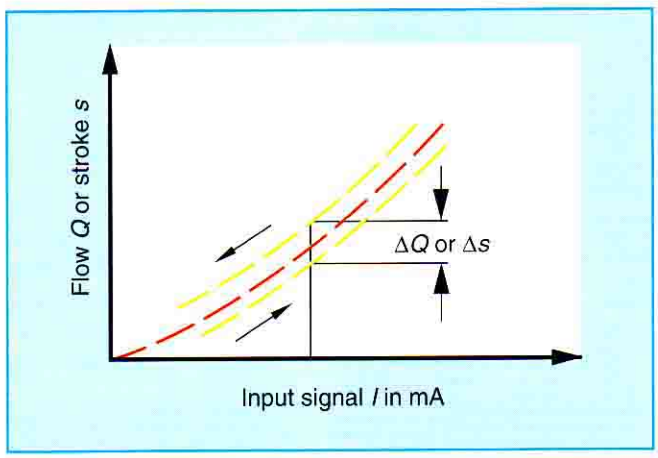
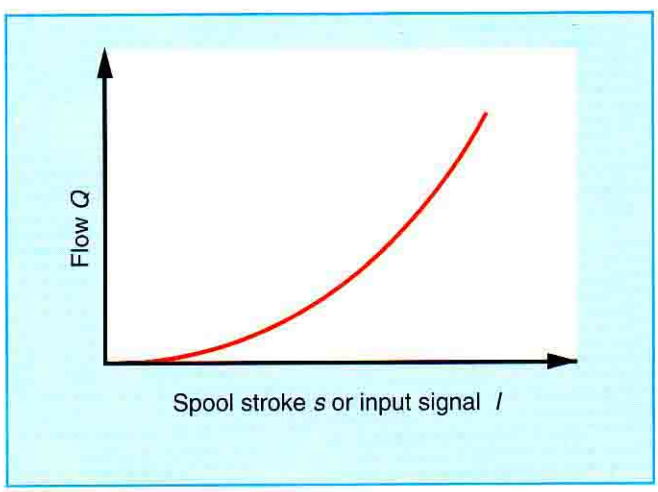


Fig. 13: *Directly operated proportional directional valve Type 4WRA 6 without feedback, electronic control VT 3013*



Diag. 3: *Hysteresis*



Diag. 4: *Characteristic Q-s, characteristic Q-I curves*

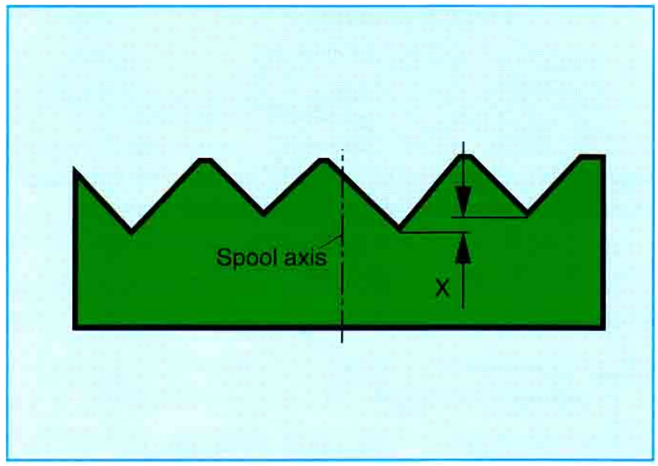


Fig. 14: *Control grooves on circumference of spool having different "start" positions and long spool stroke providing excellent resolution capacity.*

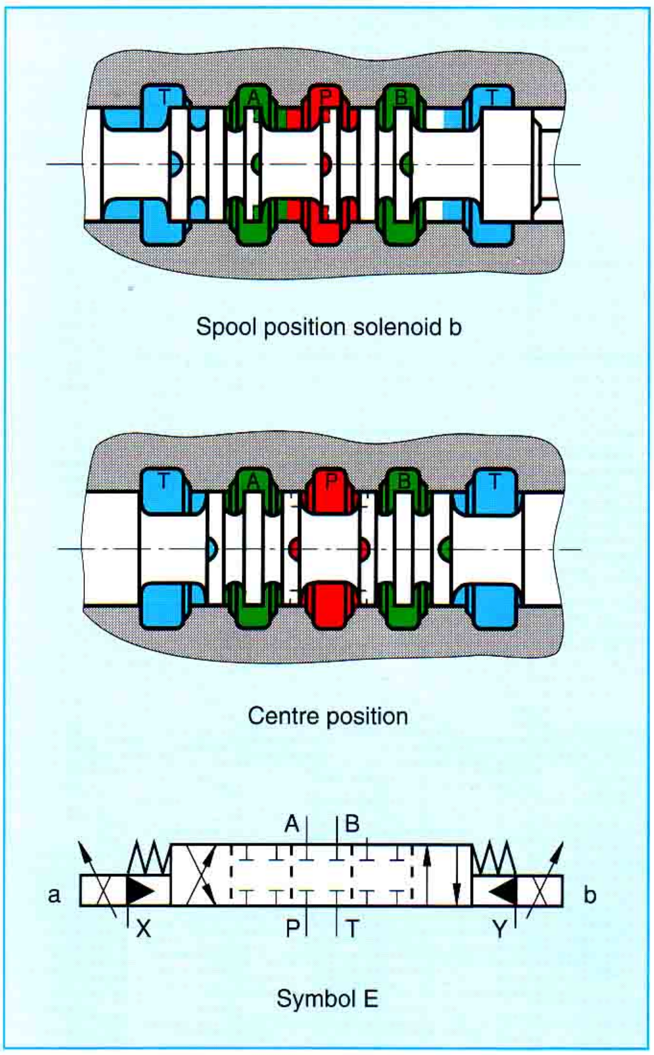


Fig. 15: *Spool overlap of a standard directional valve, size 25, symbol "E" (blocked mid-position)*

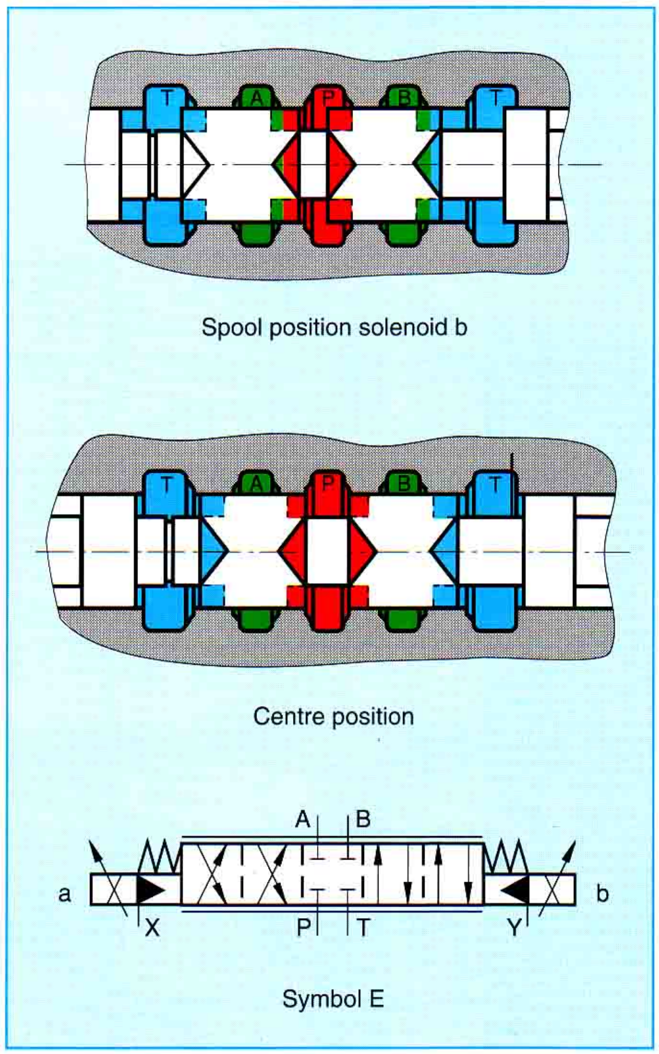


Fig. 16: *Spool overlap of a proportional directional valve, size 25, symbol "E" (blocked mid-position)*

2.1.5 Characteristic Flow Curve

To ensure the maximum spool stroke is fully utilized, corresponding control groove openings are defined for various nominal flow rates.

The following example illustrates this statement and facilitates understanding of the characteristic curves.

The following system data are provided:

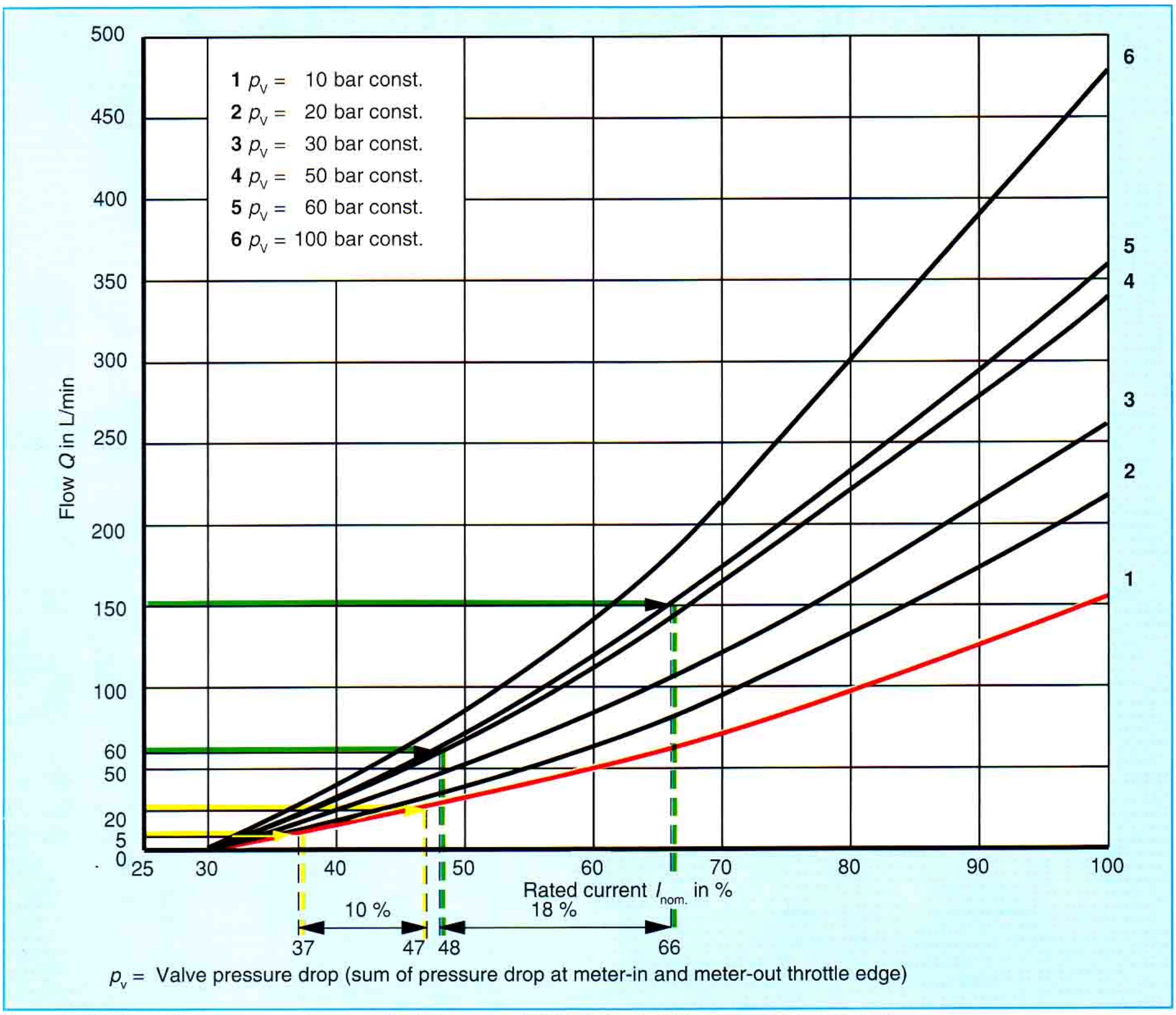
- Defined system pressure $p = 120$ bar
- Load pressure at operating speed $p = 110$ bar
- Load pressure at rapid traverse $p = 60$ bar
- Required flow rate for operating speed range $Q = 5$ to 20 L/min
- Required flow rate for rapid traverse speed range $Q = 60$ to 150 L/min

Let us assume that a proportional valve has been selected in the same way as a standard switching valve (for $Q = 150$ L/min nominal flow). This mistake, which unfortunately is made all too often, would lead to the following values:

- Valve pressure drop during rapid traverse
  $p_V = 120 - 60 = 60$ bar
  $Q_{\text{req. for rapid traverse}} = 60$ to 150 L/min
- Valve pressure drop during operating cycle
  $p_V = 120 - 110 = 10$ bar
  $Q_{\text{req. for op. cycle}} = 5$ to 20 L/min

Rapid Traverse

Referring to *diagram 5,* and allowing a pressure drop of 60 bar across the valve, a 66% signal allows a flow of 150 L/min, whilst 60 L/min is given by a signal of 48%. The effective control range is, therefore, reduced to 66 – 48 = 18% of the full range.



Diag. 5: *Flow/rated current curve for a nominal flow rate of 150 L/min at 10 bar valve pressure drop*

Operating Cycle

Allowing a pressure drop of only 10 bar, then for 20 L/min, a signal of 47% is required. As a signal of 37% is required for 5 L/min, only 10% (47 – 37) of the whole control range is available for operating speed adjustment. Taking a valve hysteresis of 3% (which is 30% referred to the 10% control range available), obvious difficulties in setting the speed would be encountered.

Diagram 6 shows the characteristic curve for a correctly selected valve:

– Characteristics during rapid traverse
  The command signal value is between 66 % and 98 % (60 to 150 L/min). This provides a setting range of 32 %.

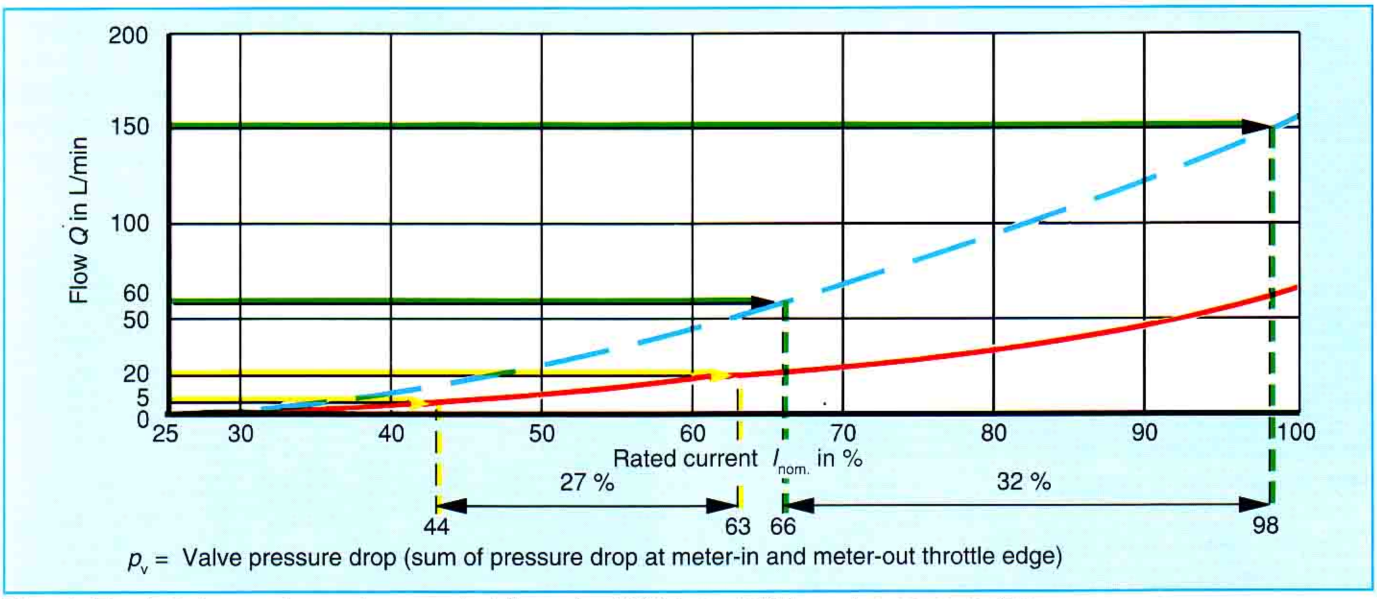
– Characteristics during operating cycle
  The command signal is now between 36 % and 63 %, i.e. providing a considerably greater setting range thereby improving the resolution. At the same time, deviations due to the repetition accuracy become smaller.

2.1.6 Time Characteristic of the Control Spool

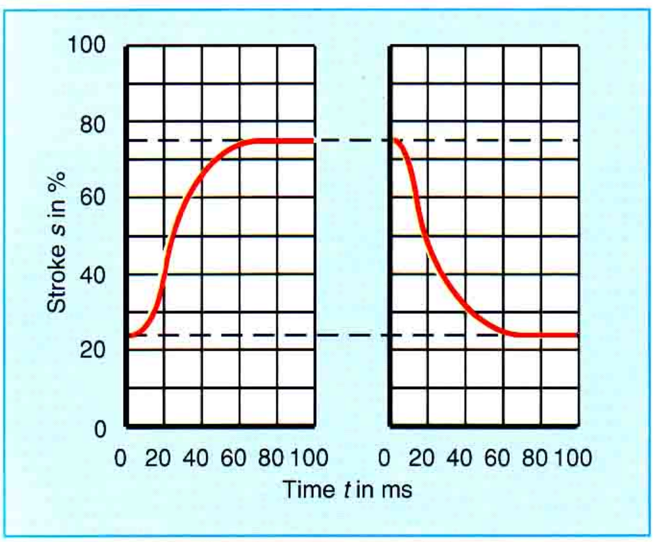
Diagrams 7 and 8 show the transfer function of the control spool in the case of a stepped electrical input signal.

The transition from one position to another position takes place without overshoot. The spool assumes the new position in a relatively short space of time, but with a damped motion.

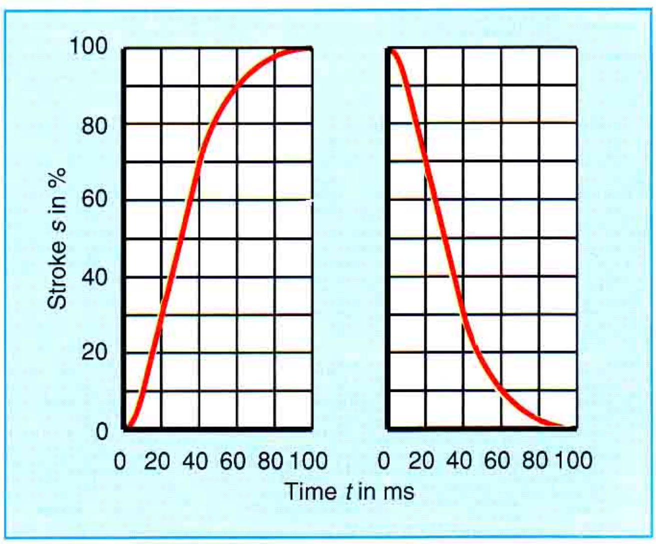
Thus the positioning time for acceleration and deceleration cycles is also more than adequate.



Diag. 6: *Flow/rated current curve for a nominal flow rate of 64 L/min at 10 bar valve pressure drop*



Diag. 7: *Transition function with stepped electrical input signal, signal change 25 to 75 %*

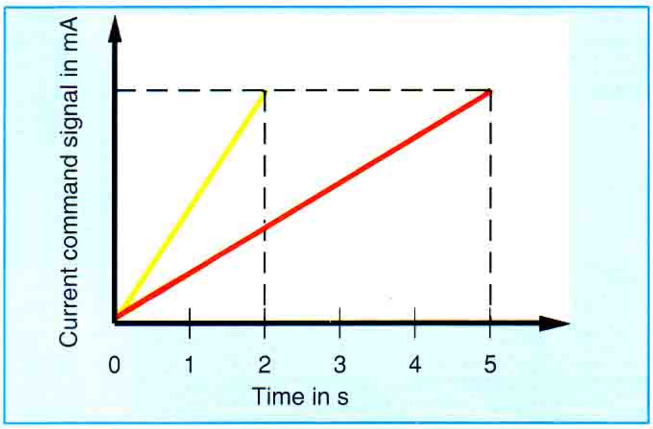


Diag. 8: *Transition function with stepped electrical input signal, signal change 0 to 100 %*

2.1.7 Acceleration, Deceleration

In the system example described in the introduction, reference was made to the acceleration of the platform with the body parts. This acceleration, i.e. also the deceleration of a hydraulic cylinder or motor refers to the change of flow per unit time. The positive or negative change in flow takes place via the proportional valve. The time, within which this change in flow and therefore the change in position of the control spool is to take place is preset at the electronic control for the proportional solenoid. The command signal provided by the electronics changes within the specified time to the value set as the final value.

This electrical component is termed the ramp generator, the time scale for the change in value is called the ramp time.



Diag. 9: *Current/time diagram*

E.g.: Change in current from

- 0 to max. in 2 s
  short acceleration time, high acceleration
- 0 to max. in 5 s
  long acceleration time, low acceleration

During deceleration, the change in command signal takes place from the high to the low value. This will be discussed in detail at a later stage in conjunction with electronic control *(refer to "Electronic Control for Proportional Valves")*.

2.1.8 Power Limits

As with the standard directional control valves, the proportional valves also have power limits which should not be exceeded. The behaviour of the directly operated valve without transducer is of particular interest in this respect. Also at a large differential pressure the flow rate does not increase beyond the power limit. The spool closes itself due to the flow forces. For this reason, reference can be made here to a "natural" power limit.

The spool or valve size to be selected for a particular system in connection with flow, depends on the system pressure to be defined. This point is discussed in detail with the aid of examples in Chapter *"Design Criteria for Open Loop Control with Proportional Valves"*.

Generally, it can be stated that a signal value of approx. 100 % should be aimed at for maximum flow.

2.1.9 Control Range (Resolution Capacity)

The term control range refers to the ratio between minimum and maximum limits of controllable flow. For the proportional directional valve without positional transducer (Type WRA) the control range is 1 : 20. At a maximum flow rate of 40 L/min for example, the minimum flow would be 2 L/min.

Of particular significance in this respect is the repetition accuracy which, expressed as a proportion of minimum flow, must lie considerably below the minimum value.

For the proportional directional valve with positional feedback (Type WRE), the control range is approx. 1:100.

2.1.10 Types of Spool

The following types of spool shown in *Fig. 17* are commonly used in practical applications:

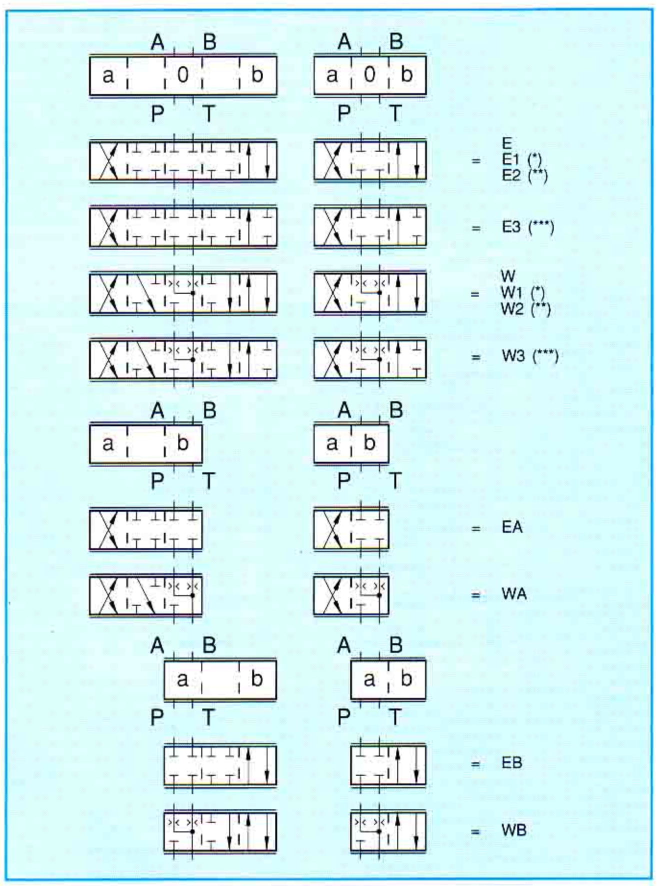


Fig. 17: *Symbols with transition functions*

(*) Symbols E1 and W1:

$P - A = Q_{max}$ | $B - T = Q/2$

$P - B = Q/2$ | $A - T = Q_{max}$

(**) Symbols E2 and W2:

$P - A = Q/2$ | $B - T = Q_{max}$

$P - B = Q_{max}$ | $A - T = Q/2$

(***) Symbols E3 and W3:

$P - A = Q_{max}$ | $B - T =$ blocked

$P - B = Q/2$ | $A - T = Q_{max}$

Fig. 18: *Flow ratios which refer to the spool symbols shown in Fig. 17*

Examples of the Individual Types of Spool

E-spool

The E-spool has the best deceleration characteristics. The openings to flow P - A and B - T as well as P - B and A - T are equal. It is therefore used in conjunction with double rod cylinders or, as shown in *Fig. 20,* with hydraulic motors.

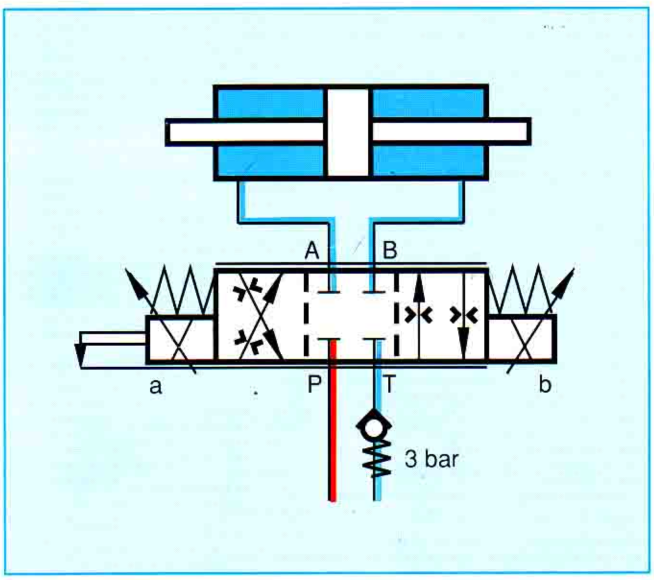


Fig. 19: *E-spool with double rod cylinder*

In the case of hydraulic motors, we recommend feed to the actuator lines as shown in *Fig. 20.*

Should a vacuum be created, the noise level of the hydraulic motor would increase considerably.

If it is necessary to hold the motor exactly in position under load, a holding brake will be required.

If the motor is not subject to load, drifting does not occur as the result of the leakage oil at the valve, since the leakage oil of the motor is greater.

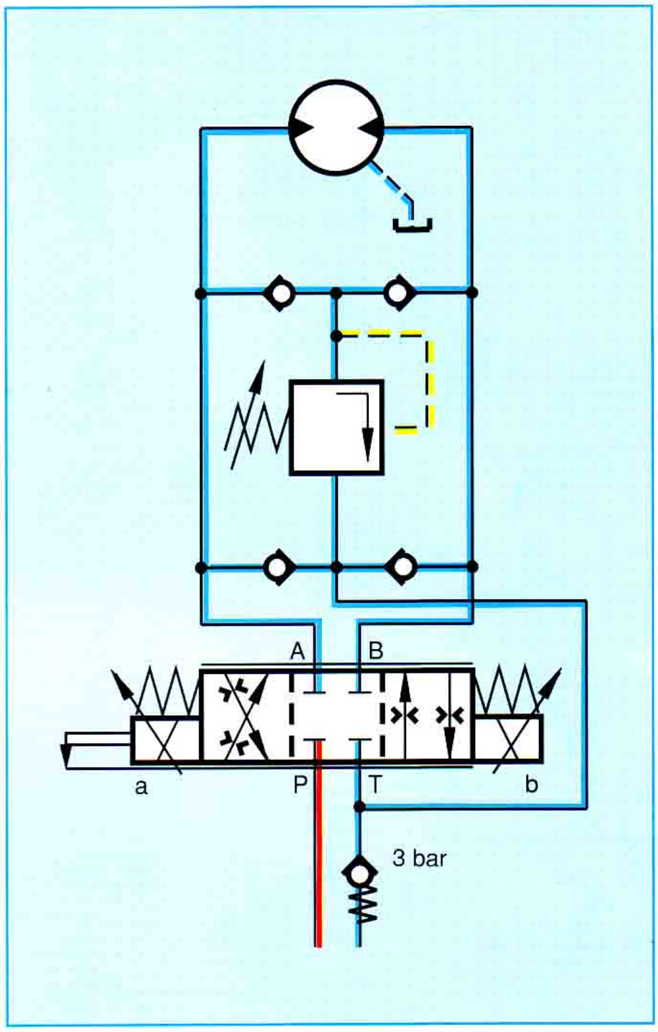


Fig. 20: *E-spool with hydraulic motor*

E1-spool

For this circuit, featuring a cylinder with a 2:1 surface area ratio, a spool should be selected with a throttle opening ratio also of 2:1. The E1-spool fulfills this requirement (also the W1-spool).

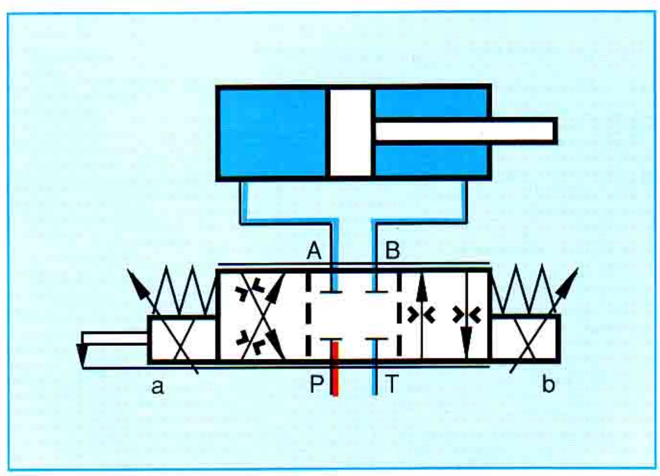


Fig. 21: *E1-spool with single rod cylinder.*

The following diagram *(Fig. 22)* illustrates the relationships. The throttle points symbolize the openings to flow in the proportional valve.

The following applies

$$\frac{Q_1}{Q_2} = \frac{\sqrt{\Delta p_1}}{\sqrt{\Delta p_2}}$$

when $Q_2 = 2 \cdot Q_1$

and the openings to flow are equal

then

$$\frac{\Delta p_1}{\Delta p_2} \triangleq \frac{Q_1^{\,2}}{Q_2^{\,2}}$$

$$\Delta p_2 \triangleq \frac{Q_2^{\,2}}{Q_1^{\,2}} \cdot \Delta p_1$$

$$\Delta p_2 \triangleq 4 \cdot \Delta p_1$$

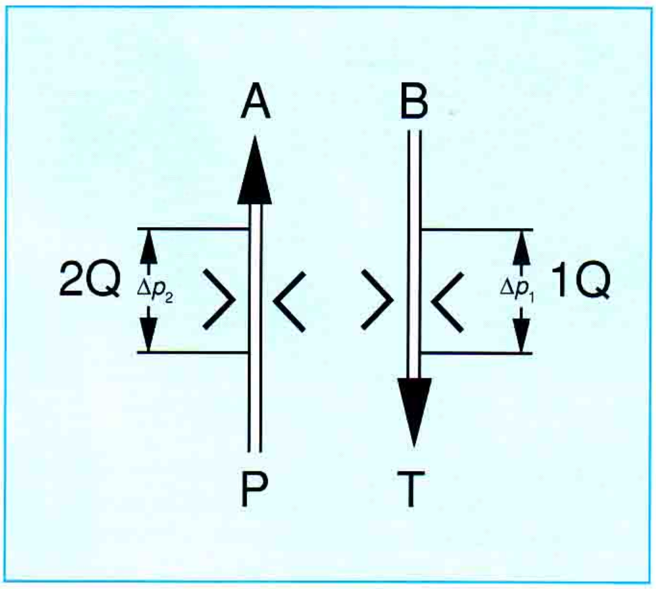


Fig. 22: *Relationship of pressure drop to flow*

This relationship clearly shows that a 4-fold pressure drop is necessary in order to achieve double the flow rate at constant opening to flow.

At a ratio of the spool area to the annulus area of 2:1, and at constant throttle opening, a differential pressure ratio of 4:1 is obtained for P - A and B - T.

If the decelerating forces of gravity acting on the piston ring side require a counter-pressure which exceeds the operating pressure by 25 %, then in this case it can be seen that the piston side is not completely filled as the result of the quadratic relationship between Δp and Q.

These problems are avoided with the E1-spool (P - A = 1/1 opening to flow and B - T = 1/2 opening to flow) or vice versa with the E2-spool.

E3-spool

(also refer to circuit with W3-spool)

It is used to obtain, by relatively simple means, a differential circuit for a cylinder with an area ratio of 2:1.

The non-return valve is also possible in the form of an sandwich plate.

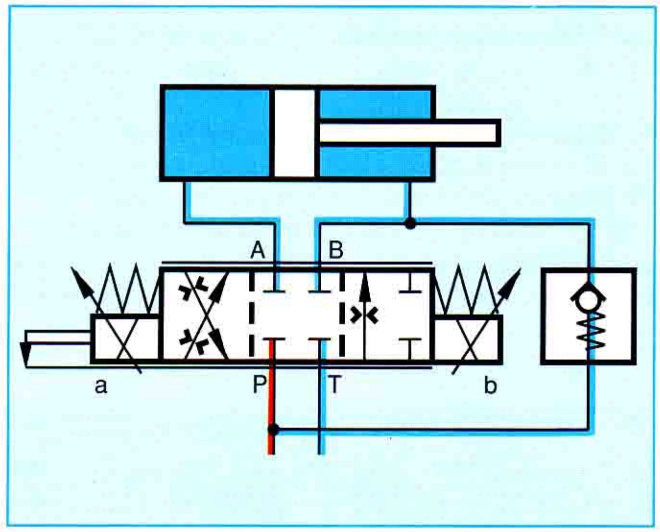


Fig. 23: *E3-spool with single rod cylinder*

W-spool

In the case of a cylinder with a single-sided piston rod and an area ratio of almost 1:1, the W-spool prevents drifting of the unloaded cylinder as the result of leakage oil. In the mid-position, a link is obtained from A and B to T at 3 % of the nominal opening.

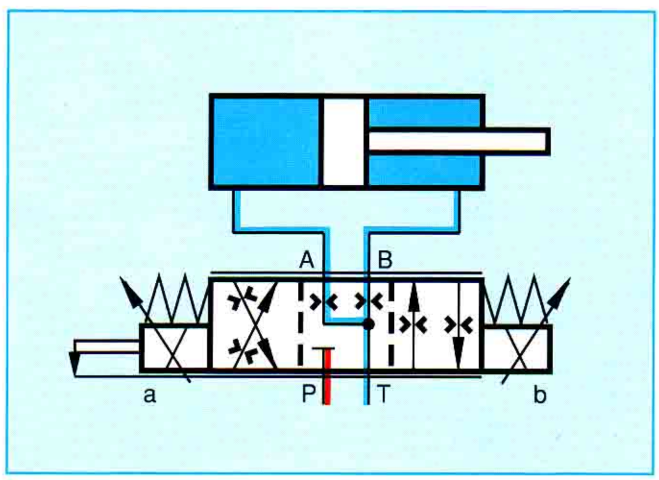


Fig. 24: *W-spool with single rod cylinder*

W1-spool, W2-spool

As the E1-spool, this spool has a throttle opening ratio of 2:1 for cylinders with an area ratio of 2:1 and as the W-spool, in the mid-position it has a link from A and B to T, amounting to 3 % of the nominal opening.

W3-spool

In the same way as with the E3-spool, the W3-spool is used to achieve a regenerative circuit. In this way, the cylinder cannot spring back after deceleration since no load is applied to B - T.

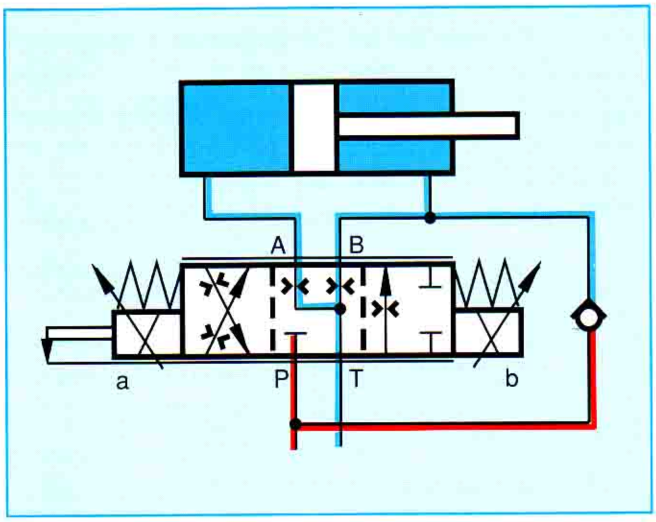


Fig. 25: *W3-spool with single rod cylinder*

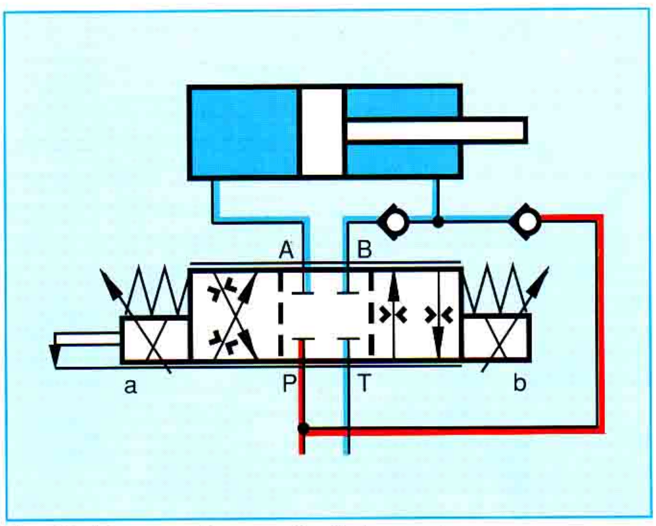


Fig. 26: *Regenerative circuit with E-spool*

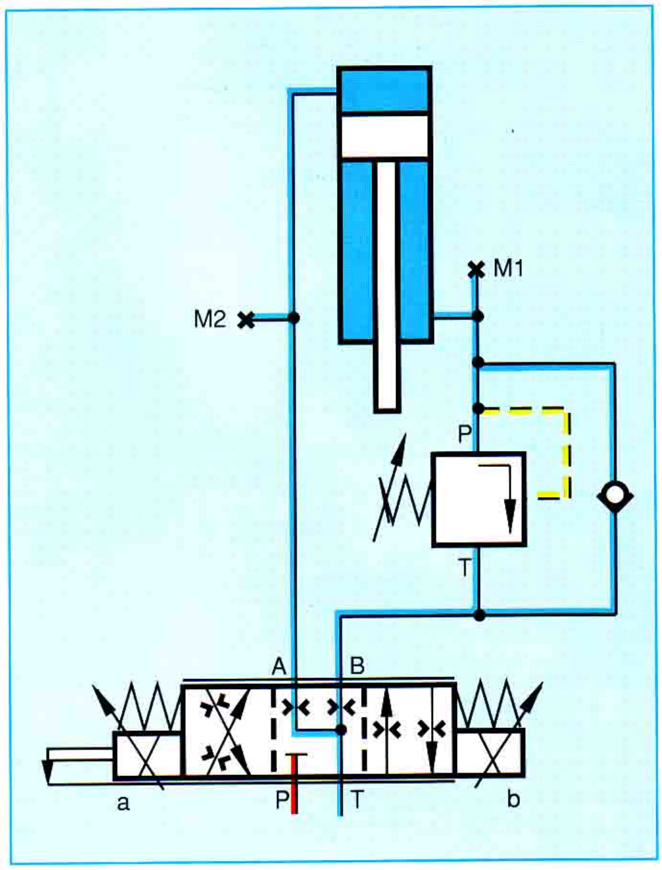


Fig. 27

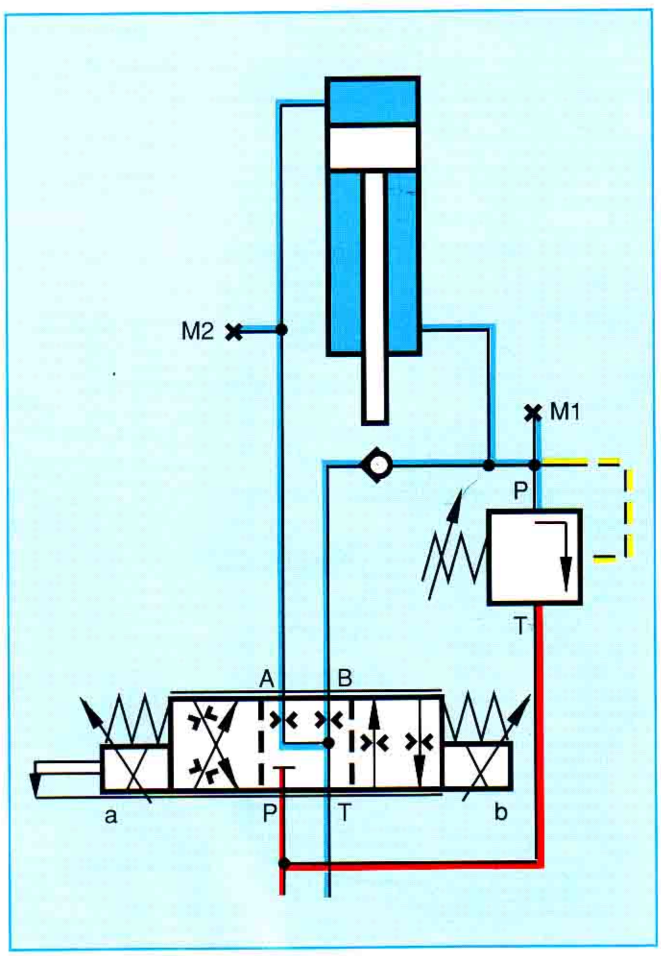


Fig. 28

Further Circuit Examples

Fig. 27: *Single rod cylinder with single rod, area ratio almost 1:1. Vertical arrangement with weight compensation. The W1-spool is used. Weight compensation is provided by a directly operated pressure relief valve (DBDs...) with leak-free cut-off of the cylinder line.*

Fig. 28: *Single rod cylinder with a Single rod, area ratio 2:1 and regenerative circuit. Vertical arrangement with weight compensation. Valve with W1-spool.*

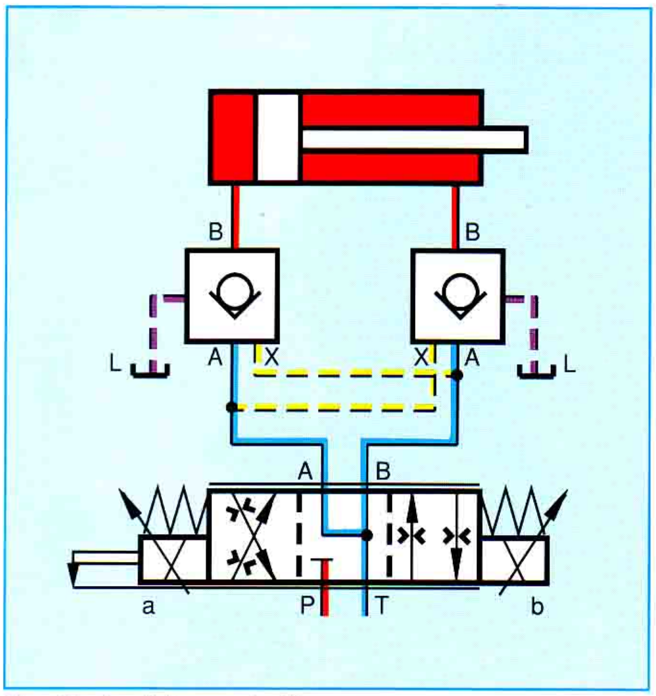


Fig. 29: *Leak-free cut-off*

Due to the pressure ratios, leak-free cut-off cannot be achieved with a twinned pilot operated check valve. In this case, it is necessary to use pilot operated non-return valves with leakage oil connection. The example shows the leakage-free cut-off for both directions of movement.

Despite the pilot operated non-return valves with external drains, particular attention must be paid to the pressure ratios in this circuit. Erratic operation may result if the pressure ratios exceed the area ratios.

In this case, the actuation of the check valves must take place externally and not, as shown, from the opposite side.

A further possibility for cut-off is offered by the meter-out throttle isolating pressure compensator *(see chapter on "Load Compensation with Pressure Compensators")*.

2.1.11 Notes on Practical Applications

Care must be taken to ensure that the valve port A is connected to port A of the cylinder, i.e. with the piston side. This applies particularly for the E1-, W1-, E3- and W3-spools and should also be considered with regard to the basic spools since A - T represents the shortest path in the valve.

Optimum dynamic values can only be achieved when the connections between the proportional valve and actuator (hydraulic cylinder, hydraulic motor) are arranged as short as possible. For this reason, the 4-way proportional valve is mainly used such that the outlets A and B are connected in the shortest possible arrangement to the two connections of a reversable displacement chamber. Only in this way does the combination of inlet and outlet resistance, coupled by the common spool allow particularly intensive influence on the movement cycle.

The maximum possible acceleration of a spring/mass system, as represented by every hydraulic system, is determined by the response time of the hydraulic unit or by the spring/mass system itself.

This is illustrated with the aid of calculation examples in the Chapter *"Design Criteria for Open Loop Control with Proportional Valves".*

2.2 Pilot Operated Proportional Directional Valve

As is the case with the conventional directional control valves, the larger sizes of the proportional valves are also pilot operated. The reason, also in this case, is due to the actuating forces necessary to shift the main control spool.

Normally, valves up to and including size 10 are directly operated, and pilot operated from this size upwards.

A pilot operated proportional directional valve *(Fig. 33)* consists of a pilot valve (3) with the proportional solenoids (1) and (2), main valve (7) with the main spool (8) and the centering spring and control spring (9).

The Proportional solenoids with force/current relationship are used.

To facilitate a general view, a simplified function sequence is described in the following:

The signal coming from the electrical control is converted in the proportional solenoid (1) or (2) into a proportional force. Corresponding to this force, a pressure is obtained at the outlet (A or B) of the pilot valve (3). This pressure acts on a surface of the main spool (8) and shifts it against the spring (9) to such an extent until a state of equilibrium is obtained between the spring force and the force generated by the pressure.

The stroke of the spool and therefore the opening to flow depends on the pressure head acting on the surface of the spool. The hydraulic pressure produced by the force controlled solenoid can be produced using either a pressure reducing, or a pressure relief principle.

The valve described in this example is equipped with a pressure reducing valve as the pilot valve. The advantage lies in the fact that pilot oil does not flow continuously through the valve.

The 3-way pressure control valve *(Fig. 31)* basically consists of two proportional solenoids (1) and (2), housing (3), a control spool (4) and 2 pressure measuring spools (5) and (6).

The proportional solenoid converts an electrical signal into a proportional force, i.e. an increase in the control current results in a correspondingly higher solenoid force. The set solenoid force remains constant over the entire control stroke.

When the solenoid is not energized, as shown in *Fig. 31,* the control spool (4) is held in the mid-position by the springs. The ports A and B are connected to port T and therefore not under pressure. Port P is closed. If, by way of example, solenoid b (1) is energized, the force of the solenoid acts via the pressure measuring spool (5) on the control spool (4) and shifts it to the right. As a result, oil flows from P to A. As before, port B remains linked to T. The pressure building up in port A acts on the pressure measuring spool (6) via the radial hole in the control spool (4). The resulting force generated by the pressure opposes the solenoid force and shifts the control spool (4) in the closed direction until a balance is reached between both forces. During this procedure, the measuring spool (6) rests on the plunger of the solenoid (2).

The link from P to A is interrupted, the pressure is held constant in the working port A. A reduction in the solenoid force results in excess pressure force at the control spool (4) so that it is shifted to the left.

Pilot oil can flow via the connected ports A - T so that the pressure can drop correspondingly.

Equilibrium of forces once again means that the pressure is maintained constant, however, now at the lower level.

In the neutral position - proportional solenoid de- energized - the ports A and B are opened to T, i.e. oil can flow unrestricted to the tank and pressure is relieved at B and A. At the same time, the link P - A or P - B is interrupted.

With the aid of the pilot valve, we can therefore vary the pressure in the ports A or B proportional to the electrical input signal.

If the chambers (10) and (12) are depressurized, i.e. A and B of the pilot valve, the main spool (8) is held in the centre position by the centering spring (9).

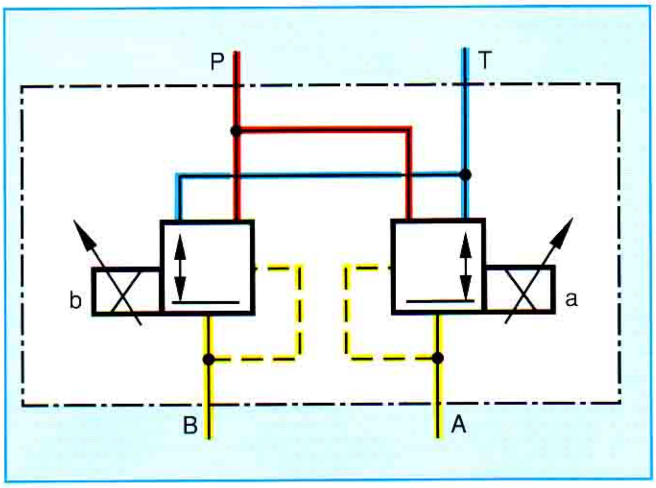


Fig. 30: Symbol for 3-way proportional pressure control valve Type 3 DREP 6 used as a pilot valve

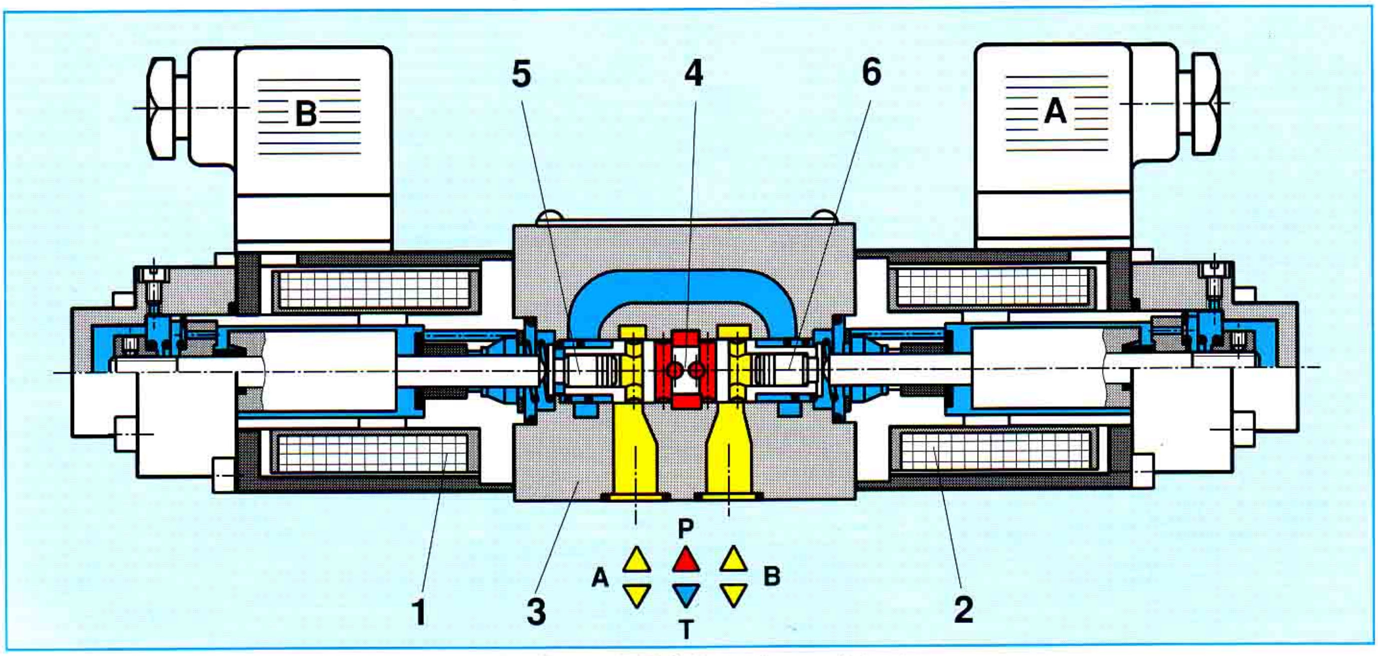


Fig. 31: 3-way proportional pressure control valve Type 3 DREP 6 used as a pilot valve.

The Effect on the Main Spool

If, by way of example, solenoid b energizes once again, pilot oil is allowed to flow either internally from the channel P or externally through the port X via the pilot valve to the chamber (10). Here pressure is built up proportional to the input signal. The resulting force generated by the pressure shifts the main control spool (8) against the spring (9) *(Fig. 33a)* until the spring force and pressure force are in equilibrium. The value of the pilot pressure therefore determines the position of the spool which in turn determines the size of the orifice-type opening and therefore the flow rate.

The design of the main control spool corresponds to that of the directly operated proportional directional valves.

If solenoid a (2) is energized, a pressure builds up in the chamber (12) corresponding to the signal. This pressure once again shifts the main spool *(Fig. 33b)* against the spring (9) via the tie-rod (13) rigidly linked to the spool.

The spring (9) is preloaded between the thrust pads and fitted without play between the cover and housing. The use of one spring for both spool directions ensures, an identical valve reaction in each direction to any given signal, and thus, equal deflection in each direction. In addition, the thrust pad mounting system allows a particularly low-hysteresis to be achieved.

The spring once again forces the control spool into the centre position when the pressure is relieved in the pressure chamber. The facilities for pilot oil feed (internal or external) as well as for pilot oil outlet (internal or external) are the same as those for conventional pilot operated directional valves.

The required pilot pressure is $p_{p\,min}$ = 30 bar and $p_{p\,max}$ = 100 bar.

The hysteresis is 6 %.

The repetition accuracy is 3 %.

The characteristic response curve with stepped electrical input signal shows also in this case that the control spool takes up its new position without overshoot *(Diag 10)*. This is due to the strong centering spring. As a result, flow forces also have no effect on the spool position.

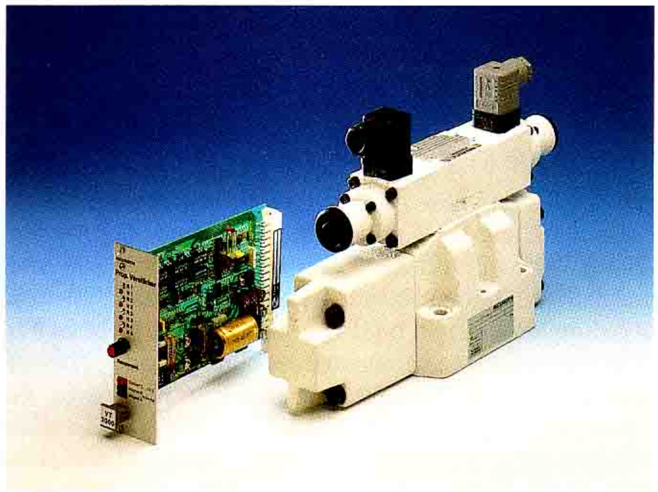
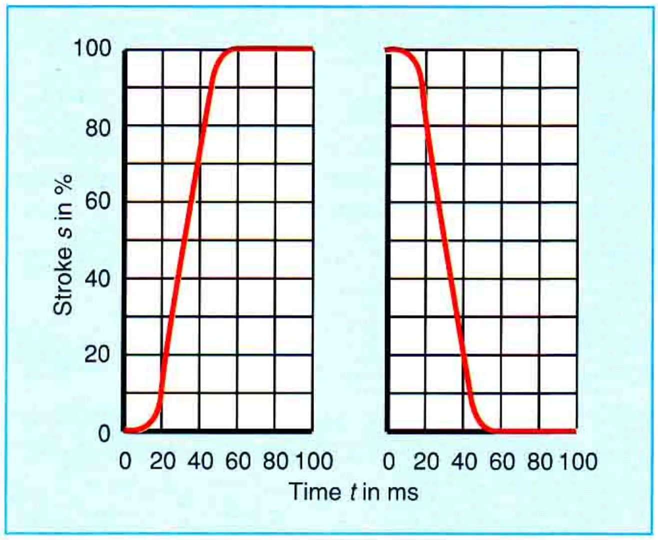


Fig. 32: *Pilot operated proportional directional valve type 4WRZ, electronic control type VT 3000*



Diag 10: *Transition function for stepped electrical input signal. Signal change from 0 to 100 %*

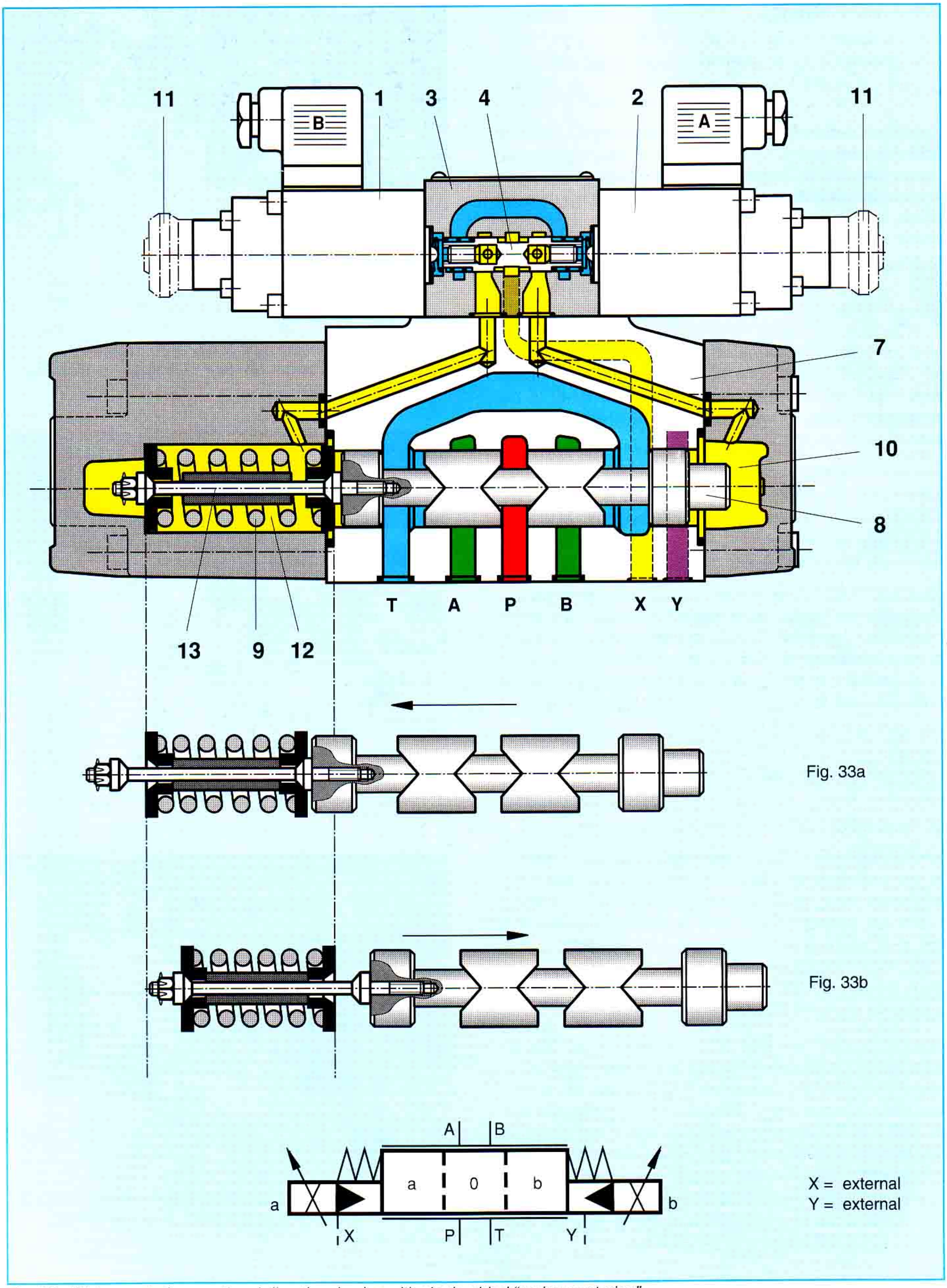


Fig. 33: *Pilot operated proportional directional valve with single-sided "spring centering"*

2.3 Summary

"Should different types of proportional valves with spool position feedback be preferred?"

It is true that the repeatability of the main spool position with electrical position feedback and constant oil temperature is within the range of 0.01 mm. However, the fact must be taken into consideration that at various oil temperatures (20 °C to 70 °C), the temperature drift of the transducer and of the tie-rod can lead to changes in the spool position which were measured to be up to 0.03 to 0.04 mm at the Mannesmann Rexroth laboratories, referred to a total stroke of 4 mm by the spool of a proportional directional valve, Type 4 WRE 10. The repeatability of the pilot operated proportional directional valves included in the Type 4 WRZ Mannesmann Rexroth range is in the region of 0.06 to 0.07 mm. In this case, there is no temperature drift, but rather a direct spring feedback. The overall stroke is specified at 5.5 mm.

The good repetition accuracy of the 4 WRZ valves is achieved by the high spring constant of the spring at the main spool in conjunction with the low friction spring centering (spherical dome) - large positioning forces relative to the possible disturbing forces.

Electrical feedback is considered necessary in the case of directly operated proportional directional valves since the relationship of the disturbing forces which occur due to the available solenoid force is particularly unfavourable (relatively small solenoid force with respect to the disturbing forces).

The high precision, narrow shaped triangular grooves in the control spools play a significant role in the good repeatability of the control process, both in the case of the directly operated and the pilot operated proportional directional valves included in the Rexroth range.

Mechanical friction, also caused by dirt particles in the oil, is of significance with regard to the repetition accuracy only when the same command signal is to be maintained over a long period of time - stick-slip effect. In view of the fast changes in the command signal, common to the majority of modern systems, the effect of the frictional value is extremely low. The valve spool is always operated above the stick-slip range.

In control processes, it is important that, in addition to good repetition accuracy and low hysteresis, the positioning device, i.e. the proportional directional valve also features good dynamics. However, this requirement can be met only incompletely with a proportional solenoid control system (inductive solenoid system). For this reason, a servo valve control system (torque motor) may also be recommended for these cases *(see Figs. 41 and 42)*. The control characteristics of these devices with feedback are improved with servo actuation.

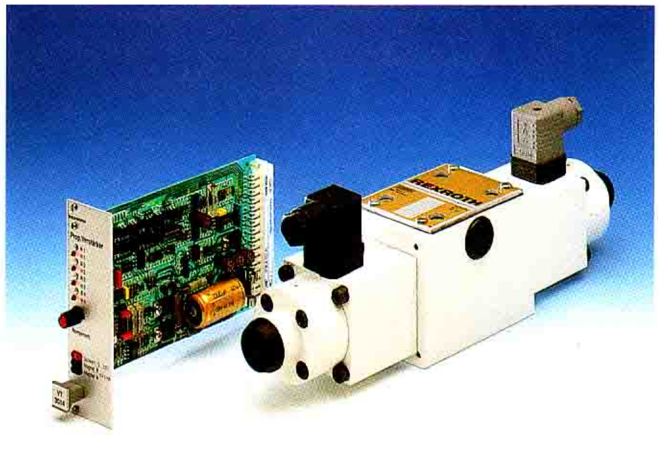


Fig. 34: *Directly operated proportional directional valve without spool position feedback, type 4 WRA 10, electronic control, type VT 3014*

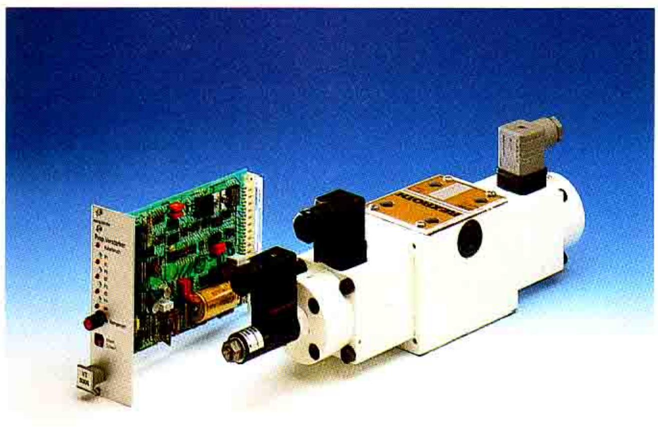


Fig. 35: *Directly operated proportional directional valve with spool position feedback, type 4 WRE 10, electronic control, type VT 5006*

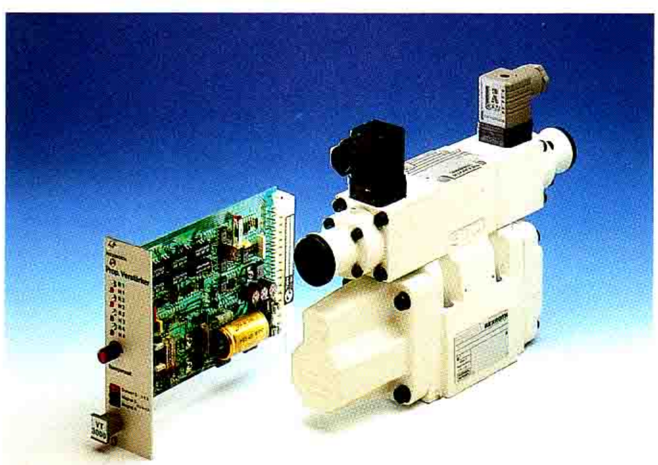


Fig. 36: *Pilot operated proportional directional valve without spool position feedback, type 4 WRZ, electronic control, type VT 3000*

The advantage of pilot operated proportional directional valves without feedback lies in their uncomplicated design and the low requirements with regard to electronic circuitry, e.g. screened cables laid separately to the positional transducer is rendered unnecessary.

It is thus not possible to make a clear cut decision for any one design on the subject of "Spool Position Feedback in Proportional Directional Valve". The best solution can be found only by taking into consideration the individual case and its requirements.

For this reason the following proportional directional valves are listed for reference:

- Closed loop control proportional directional valves 4WRK(E) *Figs. 37, 38 and 39*
  The pilot valve is a direct operated proportional directional valve.
- Closed loop control proportional directional valve 4WRT(E) *Figs. 40, 41 and 42*

  Here the pilot valve is also a servo-quality proportional directional valve with spool position feedback, powered by fast response proportional solenoids.
- Closed loop control propotional directional valve 4WRD(E) *Figs. 43, 44 and 45*
  The pilot valve is a two stage servo valve with mechanical feedback of the second stage and a flapper jet first stage valve.

All three valve variations can be supplied with electrical spool position feedback.

Optionally the electronic control can be fitted externally on a EURO-card or integrated in the proportional directional valve.

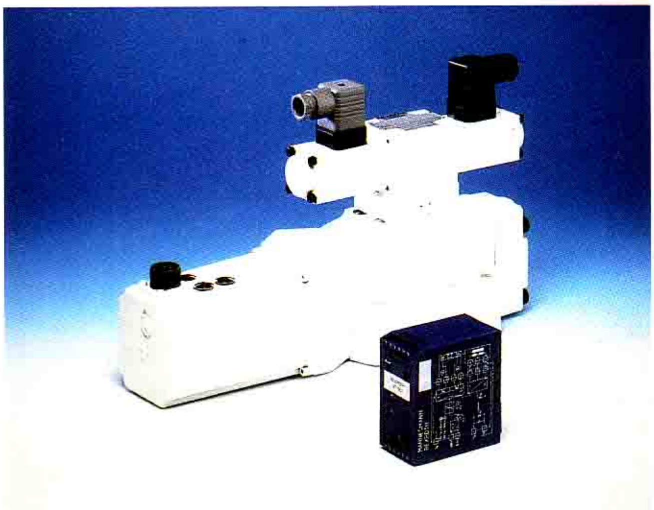


Fig. 37: *Pilot operated 4-way proportional directional valve with spool position feedback type 4 WRK with electronic control type VT 11077*

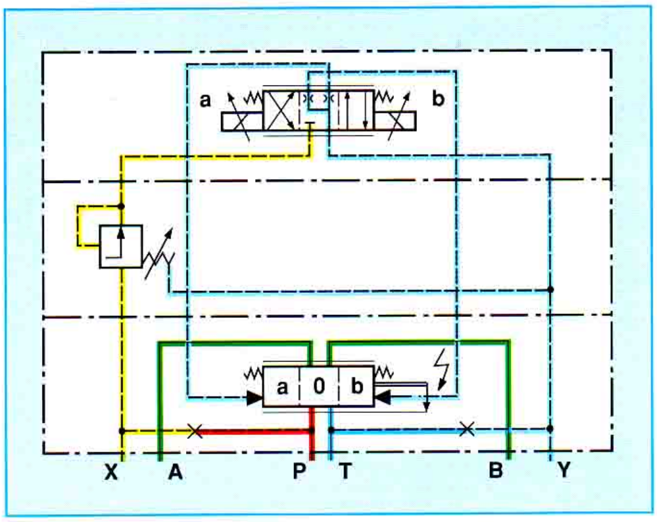


Fig. 38: *Symbol for pilot operated 4-way proportional directional control valve with spool position feedback*

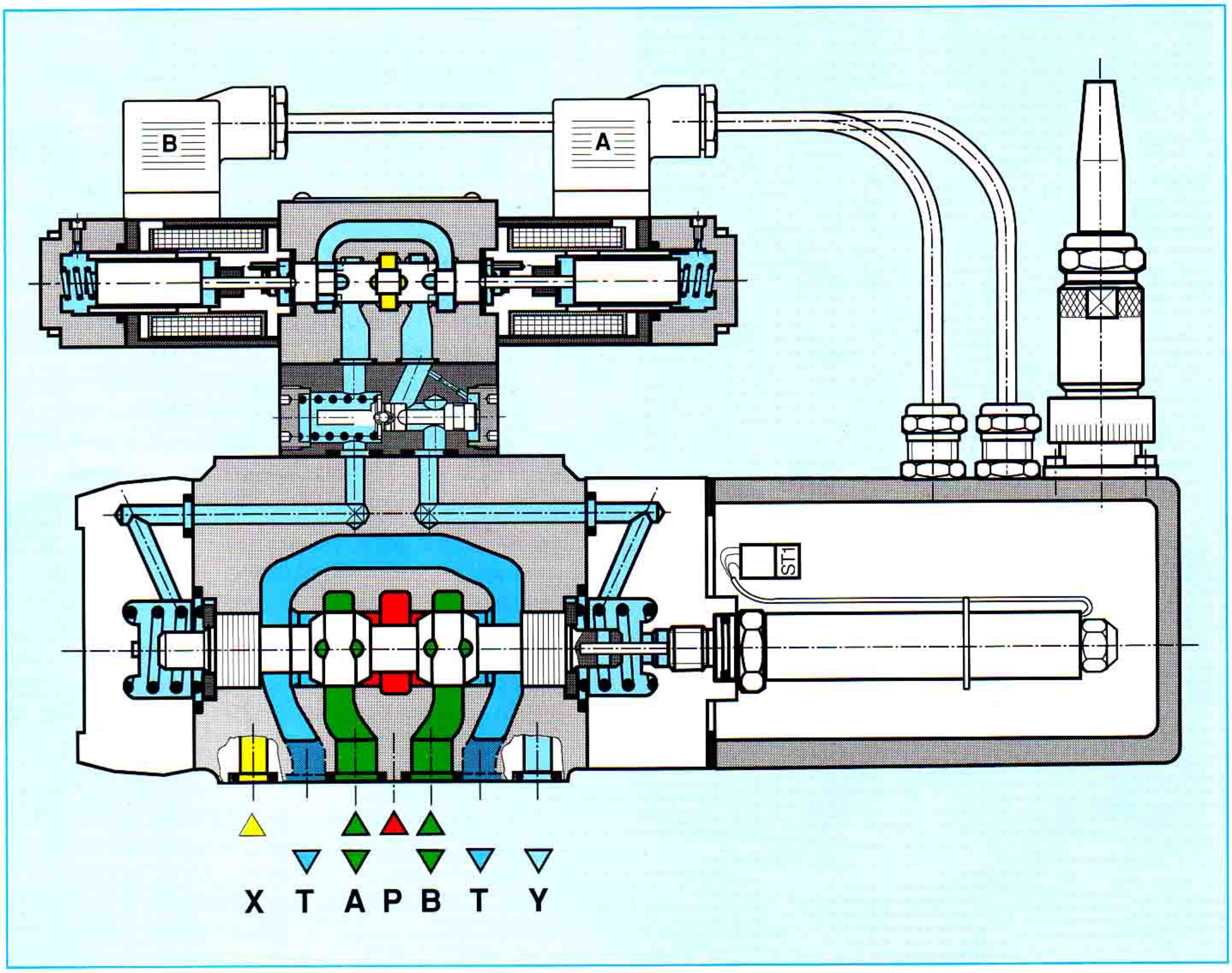


Fig. 39: *Pilot operated 4-way proportional directional valve type 4 WRKE with integral electronic control*

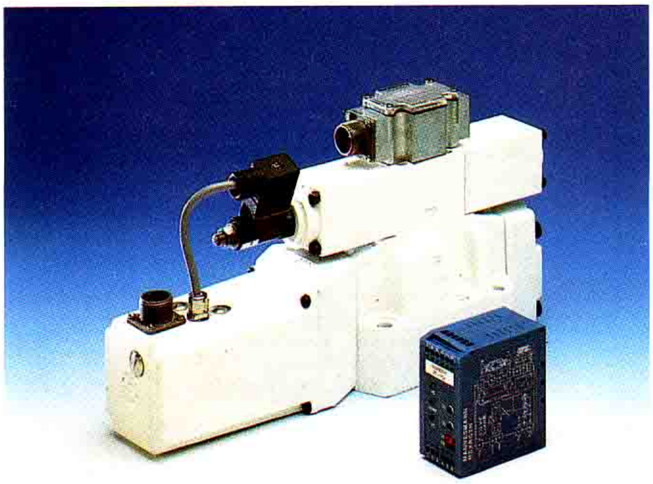


Fig. 40: *Pilot operated 4-way proportional directional valve with spool position feedback type 4WRT with electronic control type VT1101.*

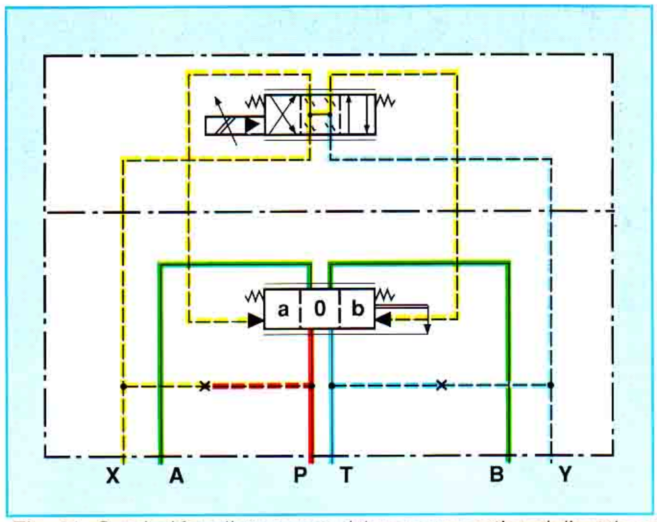


Fig. 41: *Symbol for pilot operated 4-way proportional directional valve with spool position feedback*

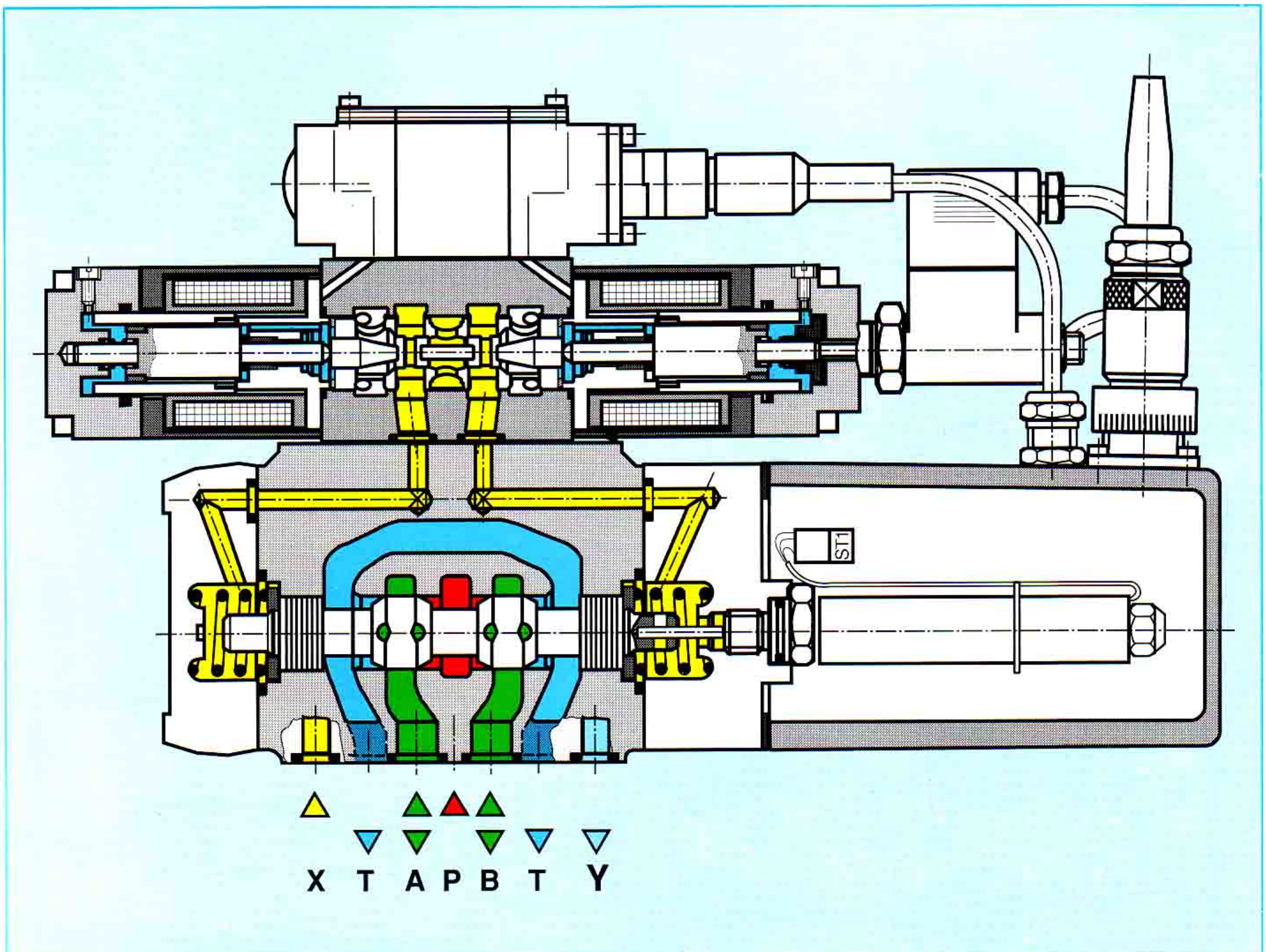


Fig. 42: *Pilot operated 4-way proportional directional valve type 4 WRTE with integral electronic control*

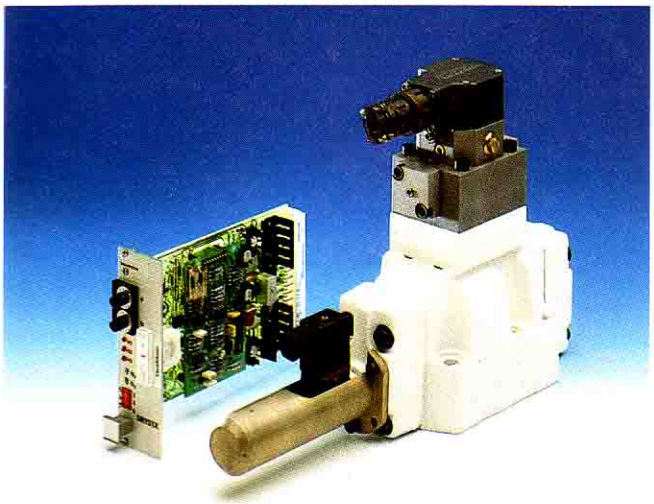


Fig. 43: *Pilot operated 4-way proportional directional valve with spool position feedback type 4WRD with electronic control type SR1*

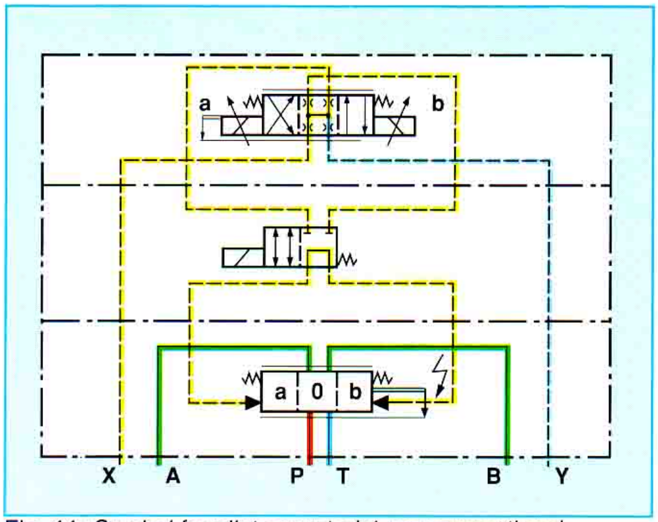


Fig. 44: *Symbol for pilot operated 4-way proportional directional valve with spool position feedback and isolator valve, sandwich plate design*

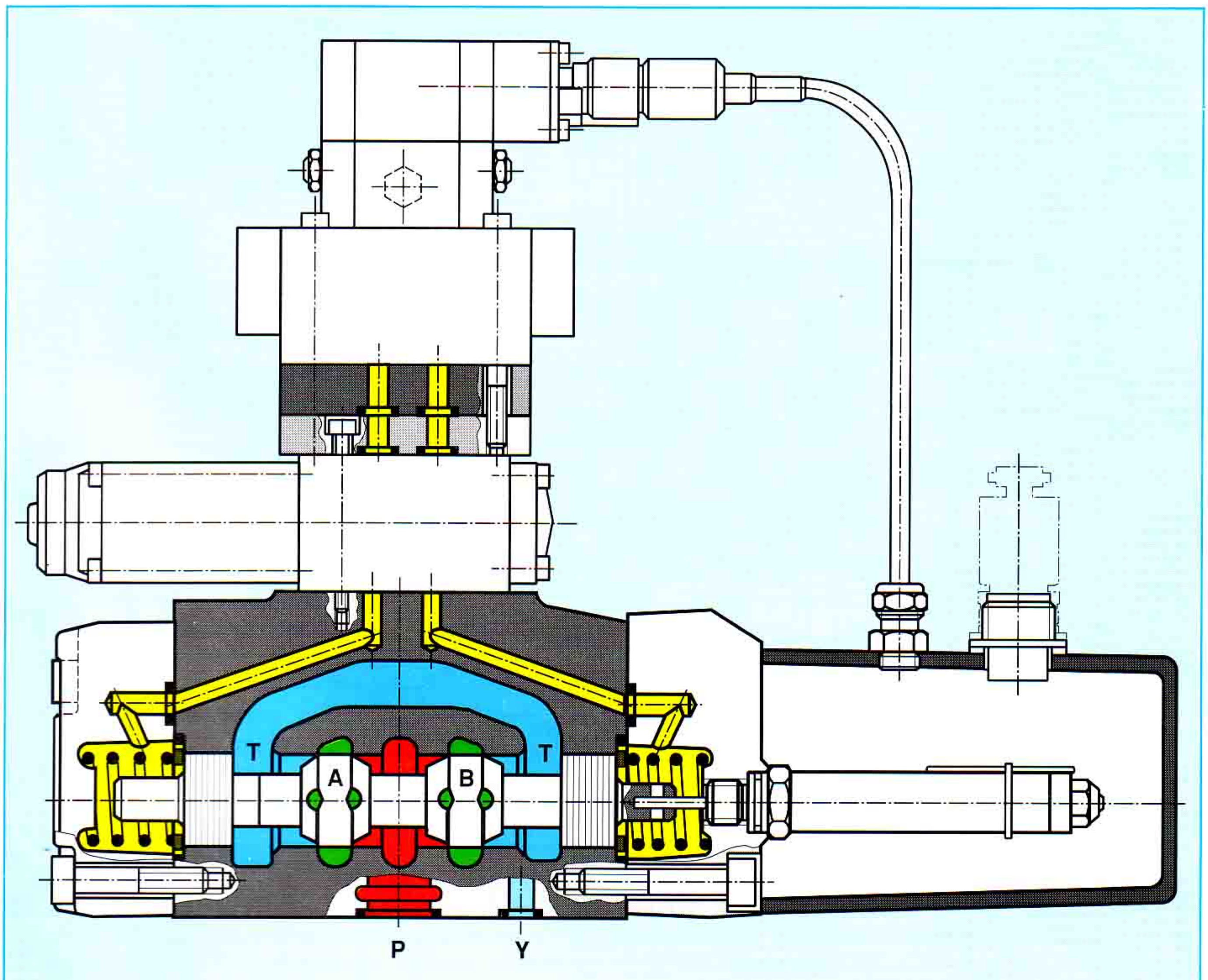


Fig. 45: *Pilot operated 4-way proportional directional valve type 4 WRDE with integral electronic control and isolator valve, sandwich plate design*

To conclude the subject of proportional directional valves, the main features are itemized in the following:

1 Concept as 4/3-way valves with spring centered mid-position.

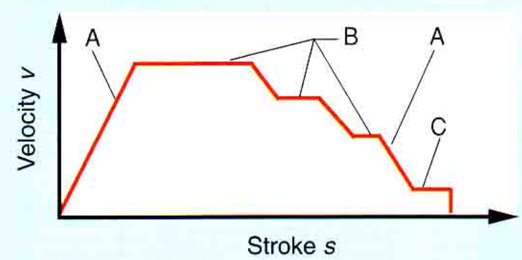
2 Low sensitivity to dirt.

3 Direction and flow control combined in one unit. With regard to program sequences, no additional directional control valves and throttles are necessary for rapid traverse and creep speeds. Speed transition not in steps but instead continuously variable.

4 Relatively long spool strokes as in simple directional valves.

5 The actuator is constantly controlled during meter-in and meter-out by two control lands.

6 In conjunction with electronic control, acceleration and deceleration procedures can be realized extremely easily and reliably.



A = Acceleration or deceleration
B = Various velocities
C = Residual velocity before stop

Diag 11: *Velocity/path diagram*

Acceleration and deceleration periods are specified by the electronics and do not depend on hydraulic influences (oil viscosity).

7 Power consumption as for DC solenoids

3 Proportional Pressure Control Valves

These valves are used for remote pressure setting by electrical means were pressure increase and pressure drop are additionally influenced with respect to time. In this way, the pressure can be changed, i.e. adapted, by means of an electrical signal corresponding to process requirements.

3.1 Directly Operated Proportional Pressure Relief Valve

The proportional pressure relief valve is designed as a poppet valve. It basically consists of the housing (1), proportional solenoid (2) with inductive positional transducer (3), valve seat (4), valve poppet (5) as well as compression spring (6) *(Fig. 39).*

The proportional solenoid is a position controlled solenoid. In this case, it replaces to a certain extent the manual setting by means of the adjusting spindle.

A signal provided via the amplifier results in a stroke at the solenoid proportional to the signal. This preloads the compression spring (6) via the spring plate (7) and presses the poppet against the seat. The position of the thrust pad (i.e. solenoid armature) and therefore indirectly the pressure setting is recorded by the inductive positional transducer and monitored by the electronic control system in a closed loop position control. Any control deviations from the signal are corrected by the closed loop control system. Solenoid friction is thus compensated resulting in a high precision, repeatable pretensioning force of the spring: hysteresis 1 % referred to max. setting pressure, repetition accuracy 0.5 % referred to max. setting pressure.

The max. setting pressure depends on the pressure rating (25 bar, 180 bar, 315 bar). The various pressure ratings are achieved by different valve seats, i.e. with different seat diameters. Since the solenoid force remains constant, the highest pressure rating has the smallest diameter.

By way of example for the pressure rating 25 bar *(Diag 12)*, it can be seen from the characteristic curves that the maximum setting pressure also depends on flow.

At command signal 0 - power failure to the proportional solenoid or cable breakage at positional transducer - the lowest setting pressure is assumed. (Dependent on the pressure rating and flow).

The spring (8) must also be mentioned in this connection. It ensures, at signal 0, that the moving parts, such as armature, are shifted back in order to always achieve the minimum value p_{min}. It also serves the purpose of compensating the weight of the armature when the valve is installed vertically.

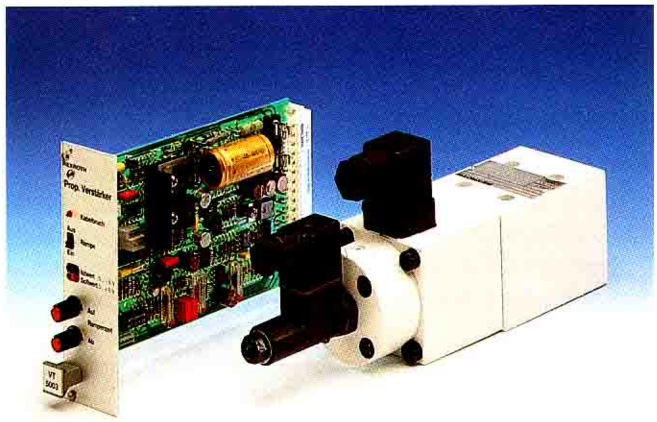
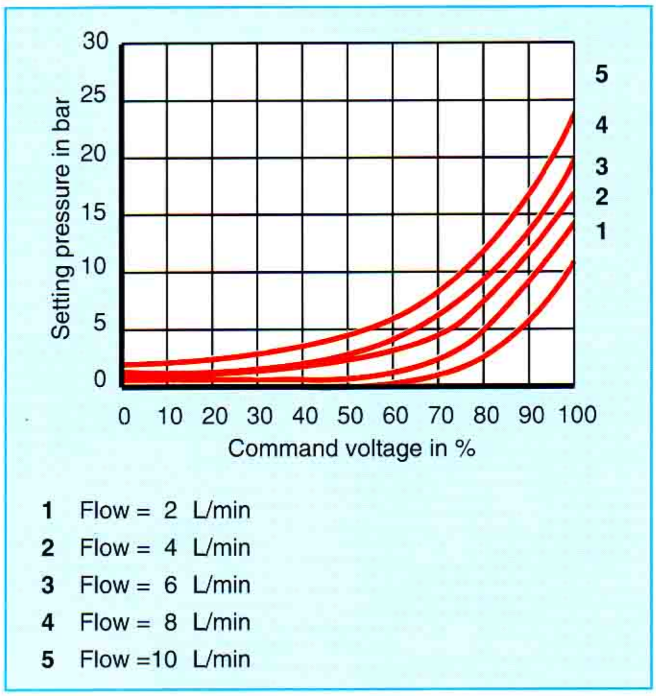


Fig. 46: *Directly operated pressure relief valve Type DBETR, control electronics type VT5003*



Diag 12: *Setting pressure dependent on the command voltage*

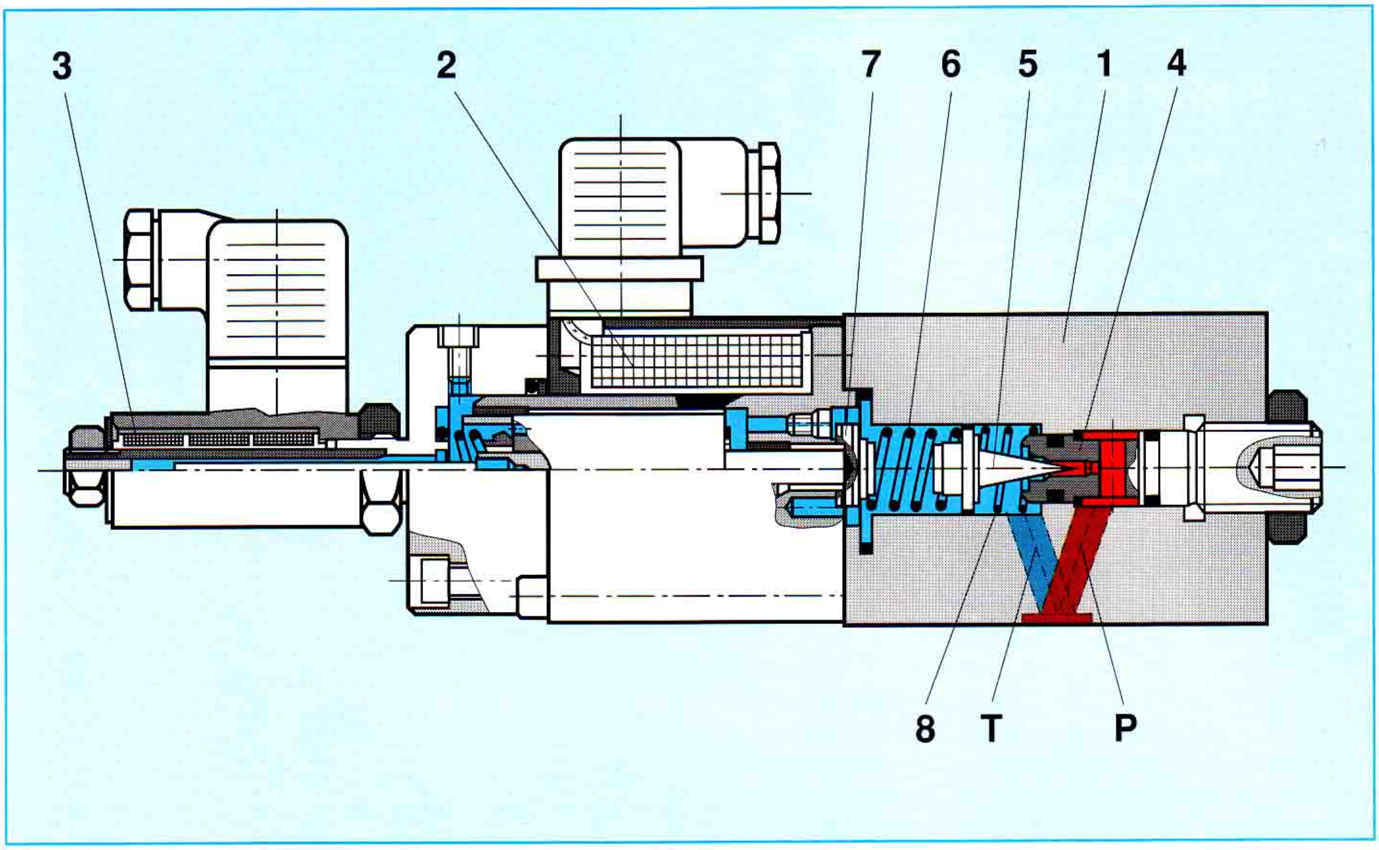


Fig. 47: *Directly operated proportional pressure relief valve Type DBETR with closed loop position control of the spring preload*

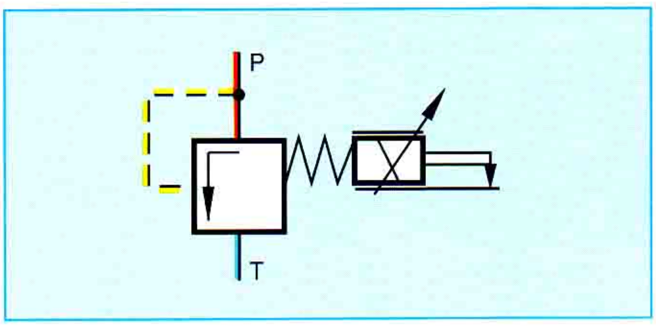


Fig. 48: *Symbol for directly operated proportional pressure relief valve, type DBETR*

3.2 Pilot Controlled Proportional Pressure Relief Valve

Pilot controlled valves are used for applications involving higher flow rates.

The valve consists of the pilot valve (1) with proportional solenoid (2), optionally with integrated max. pressure safety control (3) and main valve (4) with main spool (5) *(Fig. 51)*.

The basic function corresponds to that of the "normal" pilot controlled pressure relief valve. The difference lies in the pilot control section. In this case, the compression spring has been replaced by the proportional solenoid. It is a "force-controlled" proportional solenoid. A proportional force acting on the pilot poppet (6) therefore corresponds to a certain current, specified by the electronic control. A higher input current signifies a greater solenoid force and therefore higher pressure setting; a lower input current signifies a lower pressure setting. The pressure applied by the system (port A) acts on the main spool (5). At the same time, the system pressure is applied to the spring-loaded side of the main spool (11) via the pilot line (10) equipped with the orifices (7,8,9). This system pressure acts on the pilot poppet (6) via the orifice (12) against the force of the proportional solenoid (2). The pilot poppet (6) opens when the system pressure increases above the set value corresponding to the solenoid force. The pilot oil can flow to the tank via the port Y (13). It should be noted that flow from port Y is always at zero pressure.

Due to the orifice combination in the pilot control line, a pressure drop now occurs at the main spool (5) such that it is raised from the seat and opens the connection from A to B (pump - tank).

To safeguard the system against impermissibly high currents at the proportional solenoid (2) which would inevitably result in impermissibly high pressures, a spring-loaded pressure relief valve can be installed as an additional option in the form of a max. pressure safety control (3). This valve can also be used to safeguard the pump.

When setting the pressure for the max. pressure safety control, a certain setting clearance with respect to the max. pressure setting must be maintained at the proportional solenoid to ensure that it really only responds at pressure peaks.

As a reference value, this "safety range" should be approx. 10 % of the max. operating pressure.

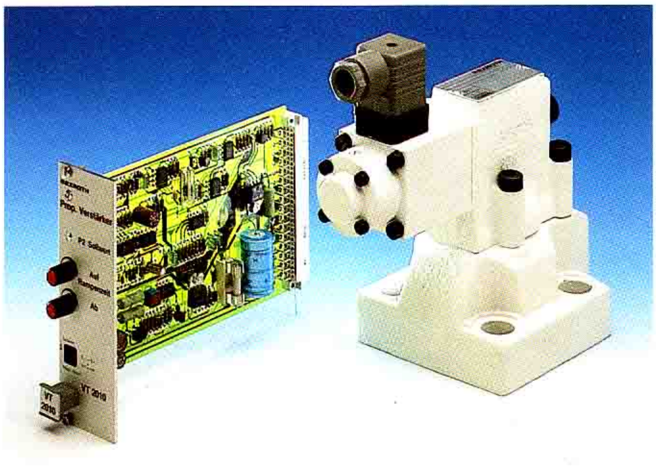


Fig. 49: *Pilot operated proportional pressure relief valve, type DBE, electronic control type VT 2010*

For example:

Max. operating pressure via electronic control = 100 bar, setting max. pressure safety control = 110 bar.

The various pressure ratings (e.g. 50, 100, 200, 315 bar) are once again achieved by means of different seat diameters. In addition to the standard characteristic curves "Operating Pressure dependent on Flow" and "Minimum Setting Pressure dependent on Flow" the relationship between input pressure and power consumption is also of considerable importance.

The characteristic curve for the pressure rating 200 bar is provided as an example in *Diag. 13*. The maximum pressure of a pressure rating is always achieved with the maximum current of 800 mA. For practical applications, this means that the pressure rating selected is on the basis of the maximum pressure required and no higher in order to obtain the best possible resolution.

The characteristic curve also shows that a higher hysteresis results when a different electronic control is used, e.g. not VT 2000 without dither current.

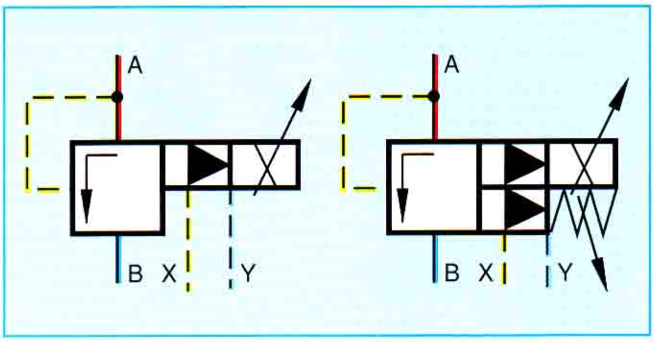


Fig. 50: *Symbol for pilot operated proportional pressure relief valve (without maximum pressure safety control on the left, type DBE; with maximum pressure safety control on the right, type DBEM).*

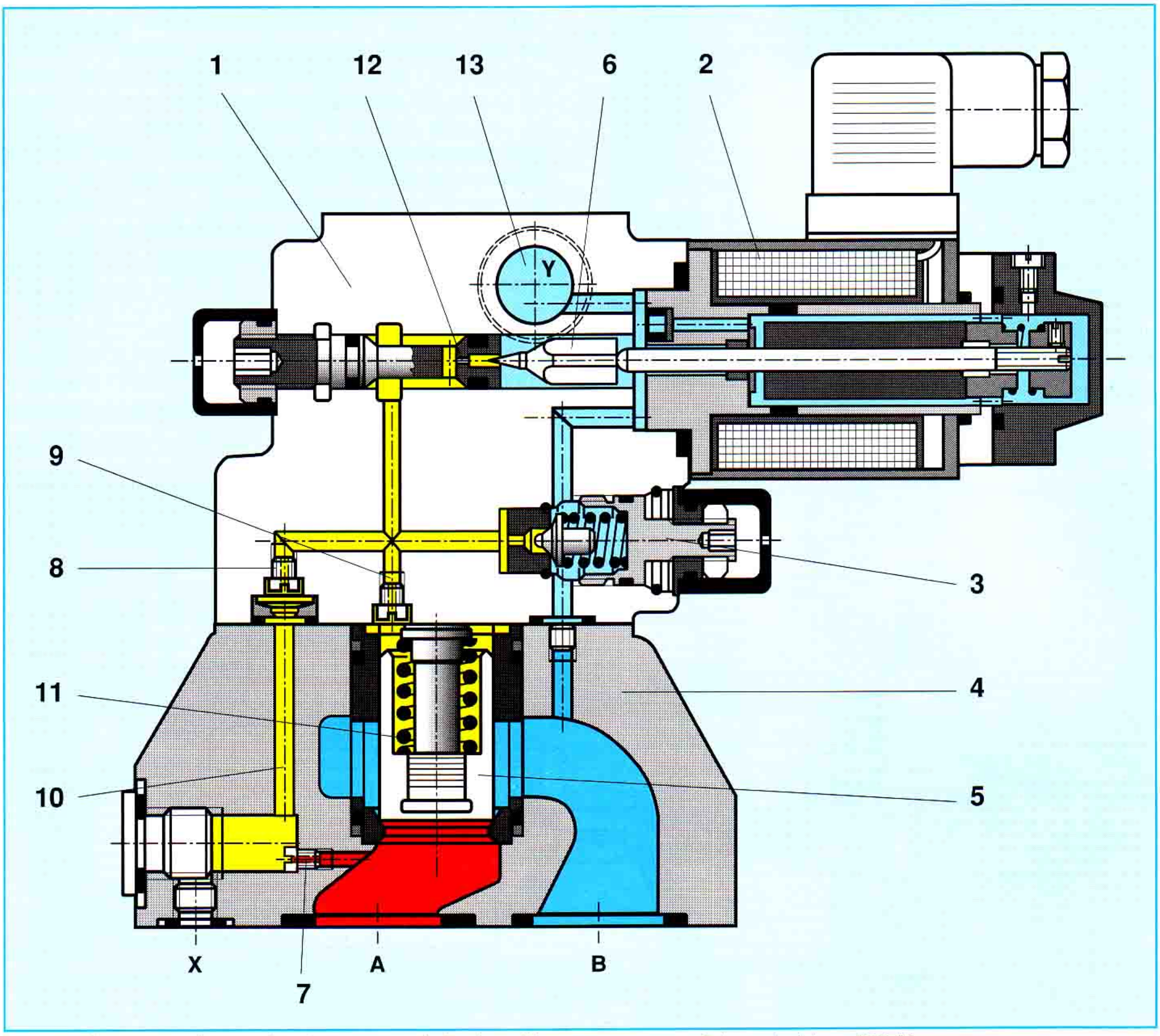
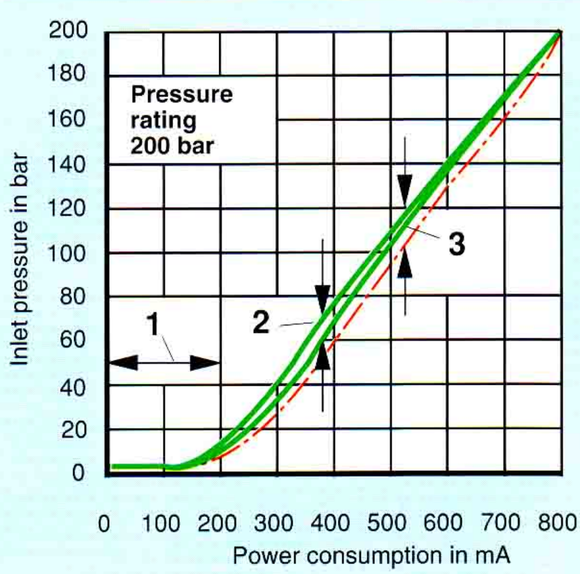


Fig. 51: *Pilot operated proportional pressure relief valve with max. pressure safety control, type DBEM*



Diag.13: *Dependency of input pressure on power consumption via example with 200 bar pressure rating*

3.3 Pilot Operated Proportional Pressure Reducing Valve, Type DRE 10, 25

As in the case of the previously described pressure relief valve, the force of the solenoid acts directly on the pilot poppet.

The pressure is set in channel A dependent on current via the proportional solenoid (2).

In the neutral position - command signal 0 (no pressure or flow at B) - the spring (10) holds the main spool in its initial position. The link from B to A is closed, so that a jump at the start is suppressed.

The pressure in channel A acts on the surface (7) of the main spool via the pilot control line (6). The control channel (8) leads from channel B through the main spool to the minimum flow control valve (9). The minimum flow control valve (9) maintains the flow of pilot oil coming from channel B constant irrespective of the pressure drop between channel A and B.

From the flow control valve (9), the pilot oil flows into the spring chamber (10) and through the holes (11) and (12) via the valve seat (13) into the Y-line (14,15,16) to the tank.

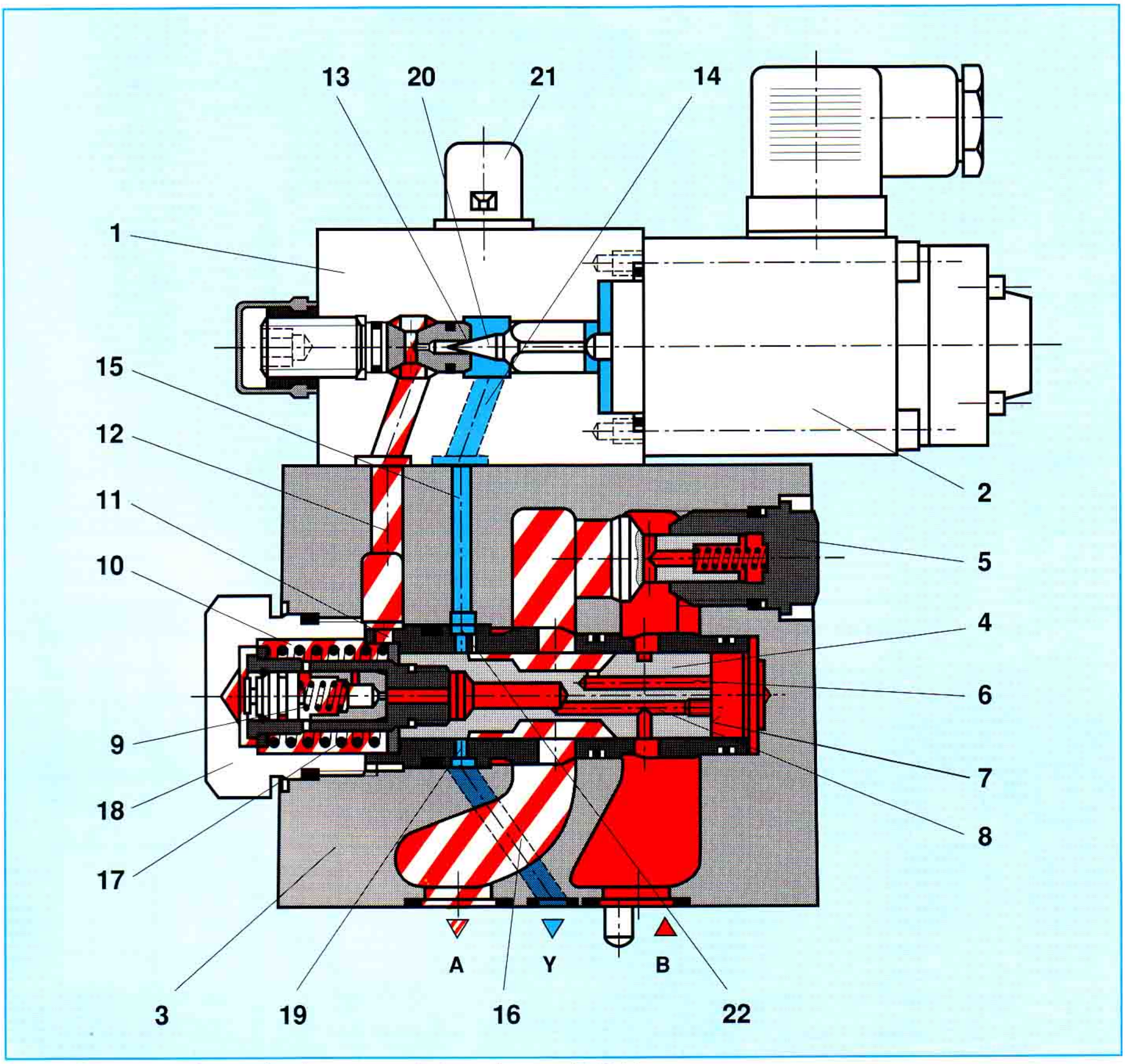


Fig. 52: *Pilot operated proportional pressure reducing valve, type DRE 10*

The pressure required in channel A is set at the corresponding amplifier. The proportional solenoid forces the valve poppet (20) against the valve seat (13), thereby limiting the pressure in the spring chamber (10) to the set value. If the pressure in channel A is lower than the set command signal, then the higher pressure in the spring chamber (10) shifts the main spool to the right. The link from B to A is opened.
There is equilibrium of forces at the main spool when the set pressure in A is reached.

Pressure in A • spool surface area (7) =
pressure in spring chamber (10) • spool surface area –
spring force (17)

If the pressure in A increases, the spool is shifted to the left in the closing direction B to A.

If the pressure in A is to be lowered in a static oil column (e.g. cylinder against limit stop), a lower pressure which is immediately applied in the spring chamber (10) is selected at the signal potentiometer of the corresponding amplifier. The higher pressure in A acting on the surface area (7) of the main spool presses the main spool as far as it will go against the screw plug (18).

The connection from A to B is closed and from A to Y opened. The force of the spring (17) now acts against the hydraulic force on the area (7) of the main spool. In this position of the main spool, the pressure medium can flow from channel A via the control land (19) to Y and then to the tank.

When the pressure in A has dropped to the pressure in the spring chamber (10) plus Δp from spring (17), the main spool closes the large control holes in the bushing at the control land A to Y.

The residual pressure difference of approx. 10 bar with respect to the new set pressure in A is now relieved via the fine control hole (22). This arrangement ensures excellent settling characteristics without dip-in pressure. A non-return valve (5) can be installed as an option to facilitate free return flow from channel A to B. A part of the flow of oil from channel A simultaneously flows via the open control land (19) of the main spool from A to Y and to the tank.

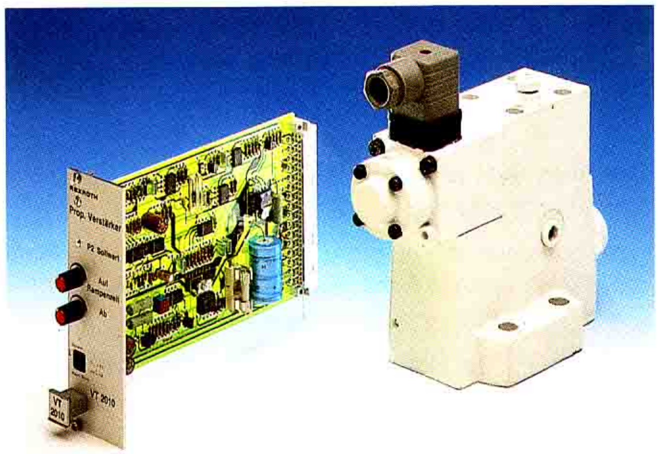


Fig. 53: *Pilot operated proportional pressure reducing valve, type DREM 20, control electronics, type VT 2010*

Type DREM

A spring-loaded max. pressure relief valve (21) can be installed on request to provide a hydraulic safeguard against impermissibly high electrical control currents at the proportional solenoid which inevitably results in high pressures in port A.

Note
When the hydraulic oil flows back from channel A to channel B via the non-return valve (5), the simultaneous parallel flow via Y to the tank influences deceleration of the actuator connected to A when deceleration is facilitated by a throttle valve (e.g. proportional directional valve) in channel B.
The third path A to Y is not suitable for limiting the pressure in channel A.

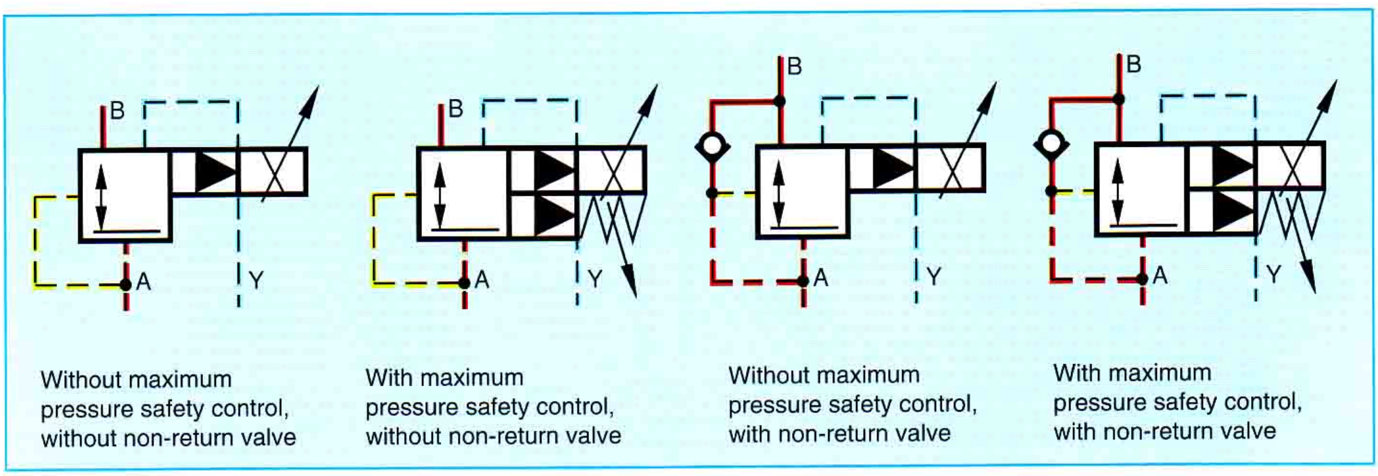


Fig. 54: *Symbols*

3.4 Pilot Operated Proportional Pressure Reducing Valve, Type DRE 30

The pressure in channel A is set current-dependent via a proportional solenoid.

In neutral position - no pressure in channel B - the main spool (4) is opened from channel B to channel A.

The pressure in channel A acts on the underside of the main spool in the closing direction, while the pressure of the pilot valve acts on the spring side of the main spool in the opening direction from channel B to A. The pilot oil is obtained from channel B and flows via the hole (6), fixed flow control (9), hole (7), valve seat (10) past the valve poppet (8) and via the Y channel to the tank.

Dependent on the electrical signal at the proportional solenoid (2), a pressure is built up at the pilot valve (1) which acts on the spring side of the main spool. In the controlled position of the main spool (4), the oil flows from channel B to A such that the pressure in channel A is not exceeded (setting of the pilot valve plus main spool spring).

If the actuator connected to port A does not move (e.g. cylinder piston against limit stop) and a lower pressure is set via the proportional solenoid (2) for channel A, then the main spool (4) closes the connection from channel B to A and at the same time opens the connection from channel A to the spring chamber of the main spool (4). In this position, the compression volume in channel A can be relieved via the pilot valve (1) and the port Y.

A non-return valve (11) can be installed as an option to facilitate free return flow from channel A to B.

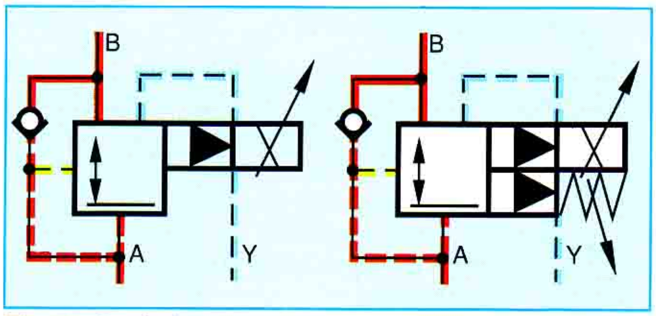


Fig. 55: *Symbols*
(without max. pressure safety control on the left; with max. pressure safety control on the right)

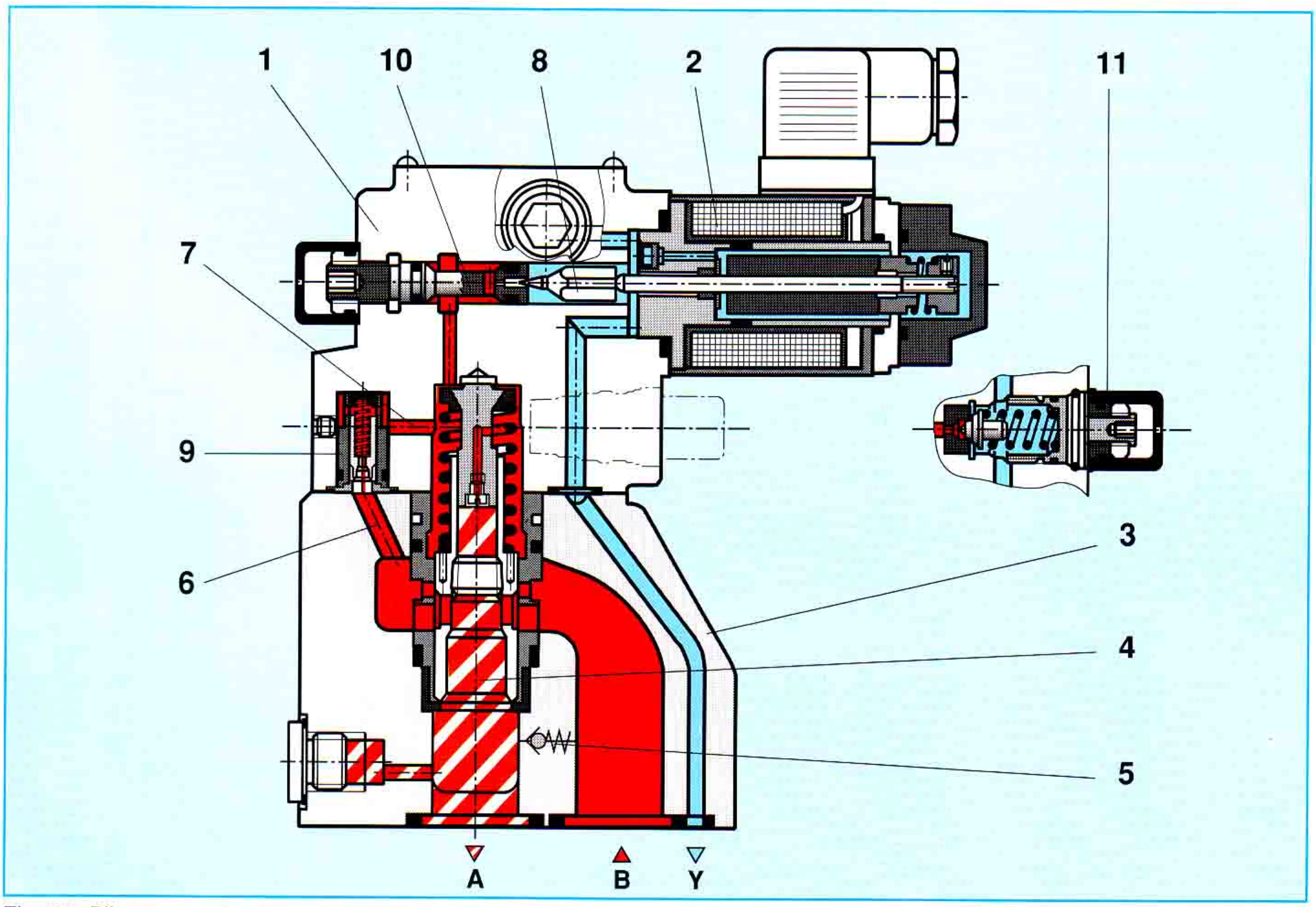


Fig. 56: *Pilot operated proportional pressure reducing valve Type DRE 30/DREM 30*

4 Proportional Flow Control Valves

4.1 2-Way Proportional Flow Control Valve with Downstream Pressure Compensator (Size 6)

The 2-way proportional flow control valve can control, independent of pressure and temperature, oil flow specified by the electrical signal. The most important components are the housing (1), the proportional solenoid with inductive positional transducer (2), the measuring orifice (3), the pressure compensator (4) as well as the optionally installed non-return valve (5).

The oil flow setting is determined by an electrical signal (command signal) set at a potentiometer. In conjunction with the electronic control (e.g. amplifier, type VT 5010), this set signal results in a corresponding current and therefore a proportional stroke of the proportional solenoid (stroke-controlled solenoid). Correspondingly, the measuring orifice (3) is shifted downwards, thereby releasing an opening to flow. The position of the measuring orifice is fed back by the inductive positional transducer. Any deviations from the command signal are corrected by the closed loop control. The pressure compensator maintains the pressure drop at the measuring orifice at a constant value. The oil flow is therefore independent of load. Good design of the measuring orifice ensures a low temperature drift.

The measuring orifice is closed when the command signal is 0 %. The measuring orifice closes in the case of power failure or cable breakage at the electrical positional transducer.

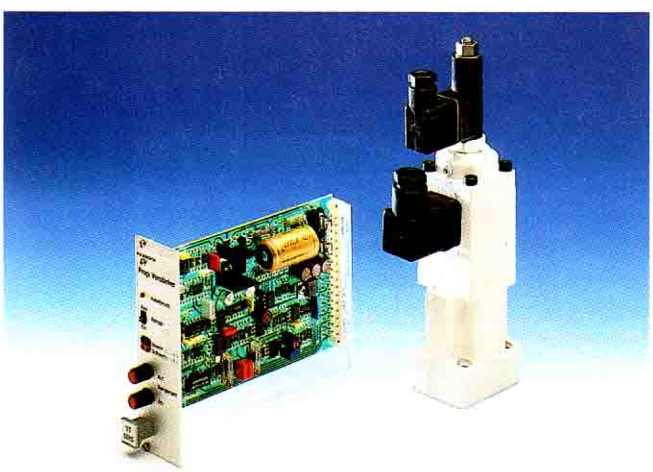


Fig. 57: *2-way proportional flow control valve, type 2FRE 6, electronic control, type VT 5010*

Starting without jump is possible from zero signal. The measuring orifice can be opened and closed with a delay via two ramps in the electrical amplifier.

Free return flow from B to A is possible via the non-return valve (5).

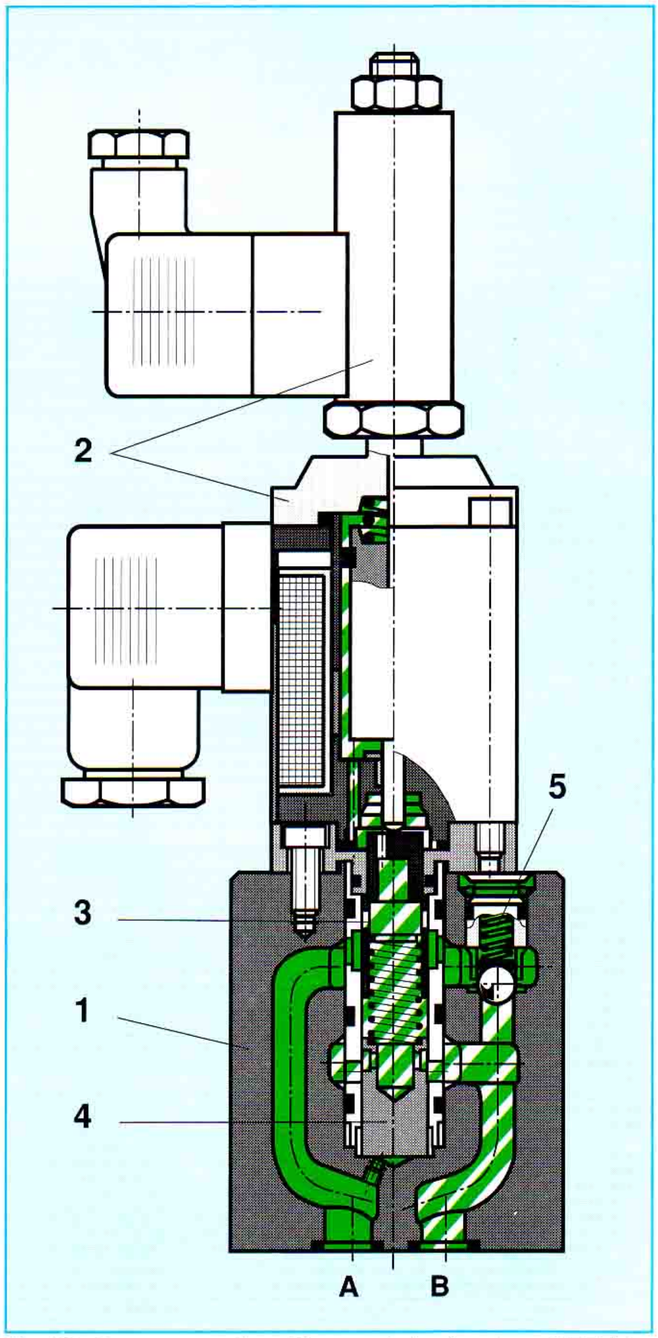


Fig. 58: *2-way proportional flow control valve, type 2 FRE 6*

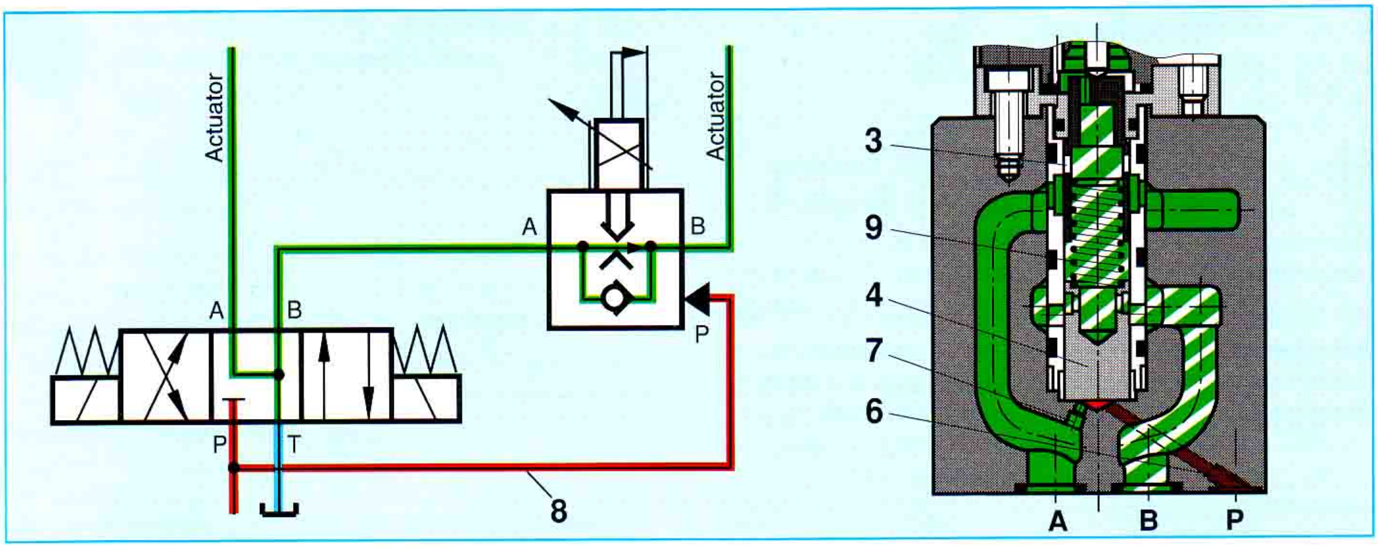
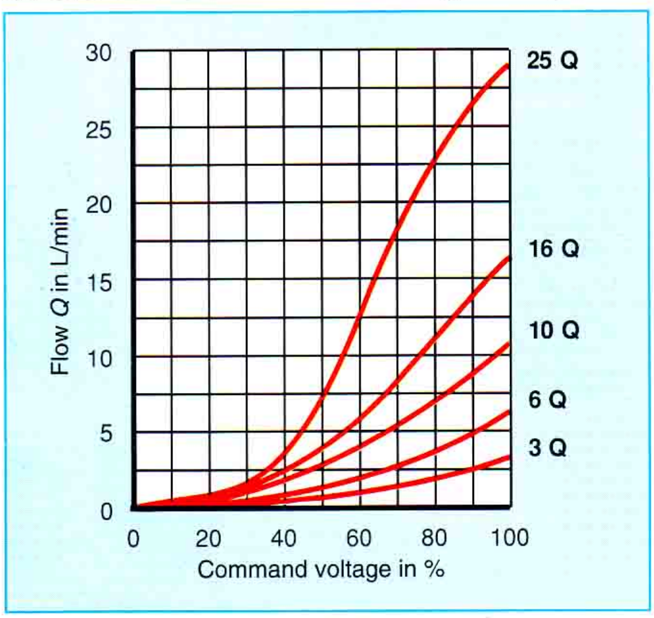


Fig. 59: *External closure of pressure compensator*

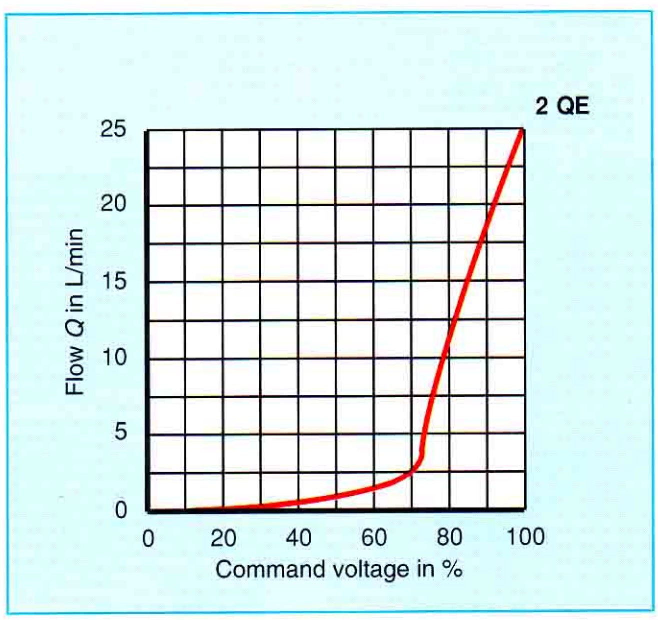
External Closing of the Pressure Compensator

The basic function corresponds to those of the 2-way proportional flow control valve already described. However, the pressure compensator (4) is closed with pressure applied via port B (6) (Fig. 51) to facilitate suppression of a jump when starting with the measuring orifice (3) open (signal > 0). The internal link (7) between port A and the effective area of the pressure compensator (4) is closed. In this way, the pressure in P prior to the directional valve (8) (see circuit example) acts via the external port P (6) on the pressure compensator (4), thereby holding it against the force of the spring (9) in the closed position. If the directional control valve (8) is shifted to the left spool position (connection P - B), then the pressure compensator (4) moves from the closed position to the controlled position so that the jump at start is prevented. Through the use of different measuring orifices, various maximum flows can be achieved at 100 % signal value. The characteristic curves in *Diag. 14* illustrate the variations.

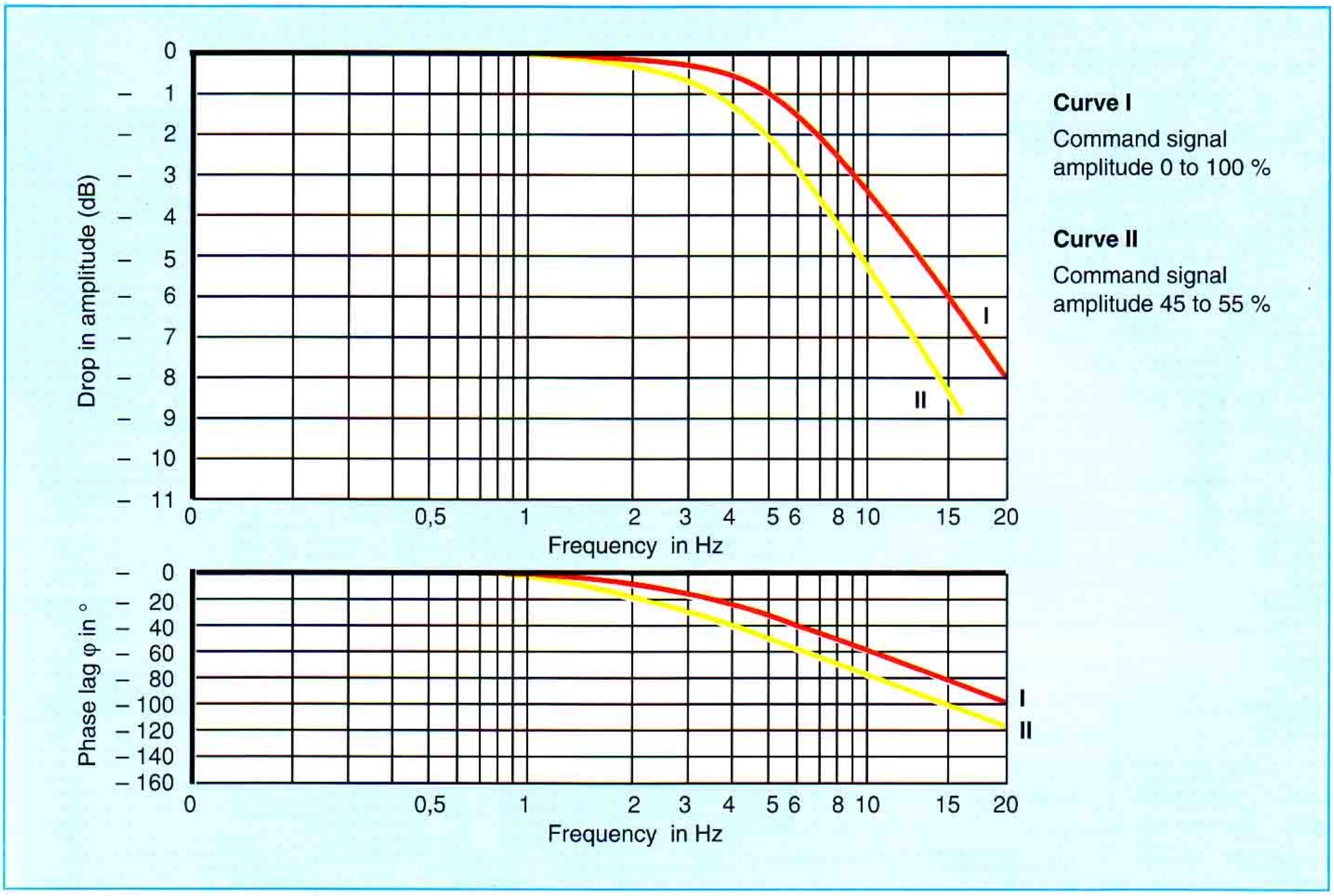
A fine control range of, for example, up to 2 L/min *(Diag.15)* can be achieved with a correspondingly designed orifice opening. The electrical signal can be infinitely varied between 0 and maximum. The frequency response (for explanation of the term frequency response refer to *"Introduction to Servo Valve Technology"*) indicates the rapidity of the valve *(Diag. 16)*.



Diag. 14: *Flow as function of command voltage with progressive characteristic*



Diag. 15: *Flow as function of command voltage for valves with progressive characteristic and stepped rapid traverse*



Diag. 16: *Frequency characteristics*

Step response in %	Q_{min} to Q_{max} $T_u + T_g$ in ms	Q_{min} to Q_{max} $T_u + T_g$ in ms
0 to 100	50	60
10 to 90	45	50
25 to 75	40	45

T_u = Time delay; T_g = Compensation time

Table 1: *Dynamics table*

4.2 2-Way Proportional Flow Control Valve with Upstream Pressure Compensator (Size 10 and 16)

This type of valve is only described in the following for the sake of completeness. “Only”, not because it is of little significance but rather because the electrical signal conversion and the hydraulic section are well known. The opening to flow is changed by means of the stroke of the stroke-controlled proportional solenoid. The flow control function is obtained by the interaction of the throttle orifice and pressure compensator.

The characteristic flow curves can be linear or progressive depending on the shape of the orifice.

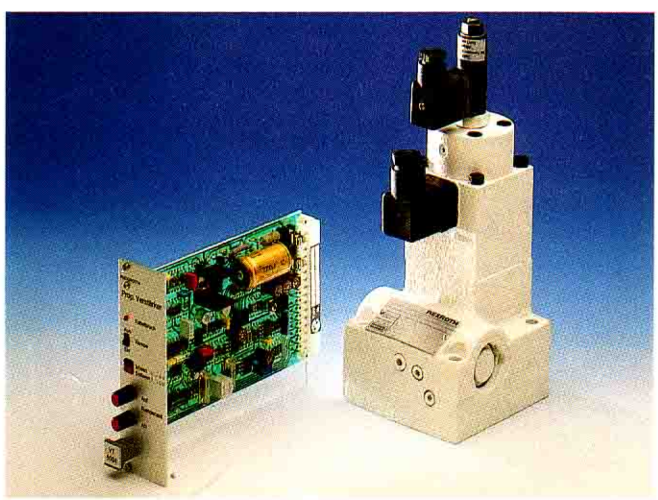


Fig. 60: *2-way proportional flow control valve, type 2FRE 10, electronic control, type VT 5004*

4.3 2-Way Proportional Throttle Valve (Cartridge valve)

This combination unit, can be used as a throttle (orifice) or in conjunction with a pressure compensator for controlling high flows. The applications include, for example, control systems for presses and plastic processing machines. Despite the high flow rates, the unit has a fast response time.

The 2-way throttle valve is an orifice with its opening stroke determined by an electrical signal. The throttle valve is supplied as a unit ready for installation with installation dimensions to DIN 24 342. The bushing (2) is screwed into the cover (1) together with the orifice spool (3) as well as the positional transducer (4) and the pilot control (5), including proportional solenoid (6).

The direction of flow is from A to B. The pilot oil port X is linked to the port A. The pilot oil outlet Y should be routed to the tank at zero pressure.

At zero signal (no current applied to proportional solenoid (6)) the pressure in port A acts via the pilot line X and the control spool (10) in addition to the spring in chamber (8). The orifice spool (3) is held closed. If a signal is fed to the amplifier card, the command signal (external signal) is compared in the amplifier (7) with the actual signal (feedback of the transducer signal). The proportional solenoid (6) is energized with a current corresponding to the differential value.

The solenoid shifts the spool (10) against the spring (11). As the result of interaction between the throttling points (13) and (14), the pressure in the spring chamber (8) is set such that the spring-loaded orifice spool (3) assumes a position corresponding to the preset signal and therefore determines the flow.

The orifice spool closes automatically (for safety) in the case of power failure or cable breakage. The components of the closed loop position control are designed such that the command signal and the stroke of the orifice spool (3) are directly proportional with respect to each other. Consequently, for constant pressure differences at the orifice, the flow from A to B is only dependent on the stroke of the orifice spool and the window geometry (9).

Direct proportionality between the signal and flow is applicable to the system with linear opening law (FE..C1X/L). The quadratic opening law (version FE..C1X/Q) signifies a volumetric flow increasing quadratically with the command signal.

The two characteristic curves illustrate this fact.

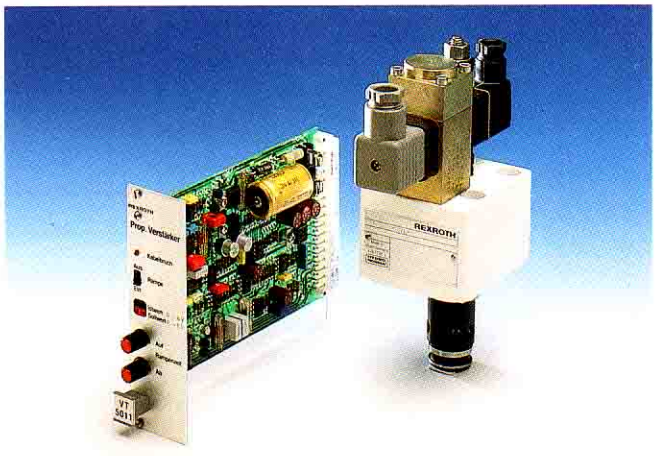
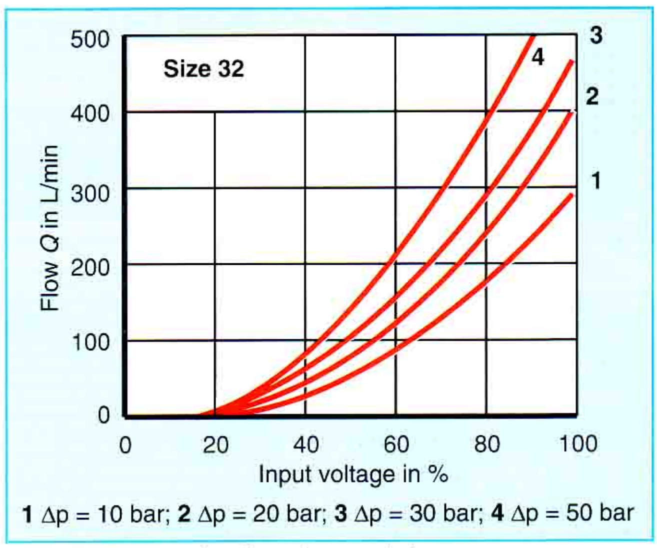
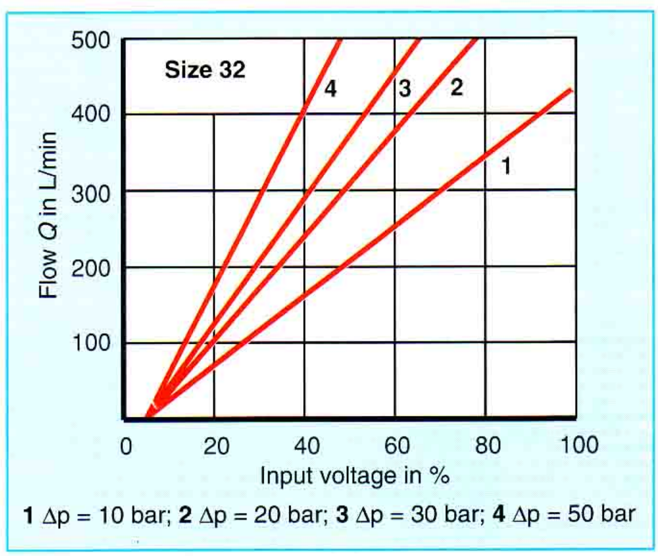


Fig. 61: *2-Way proportional throttle valve, type FE..C, electronic control, type VT 5011*



Diag 17: *Progressive flow characteristics*



Diag 18: *Linear flow characteristics*

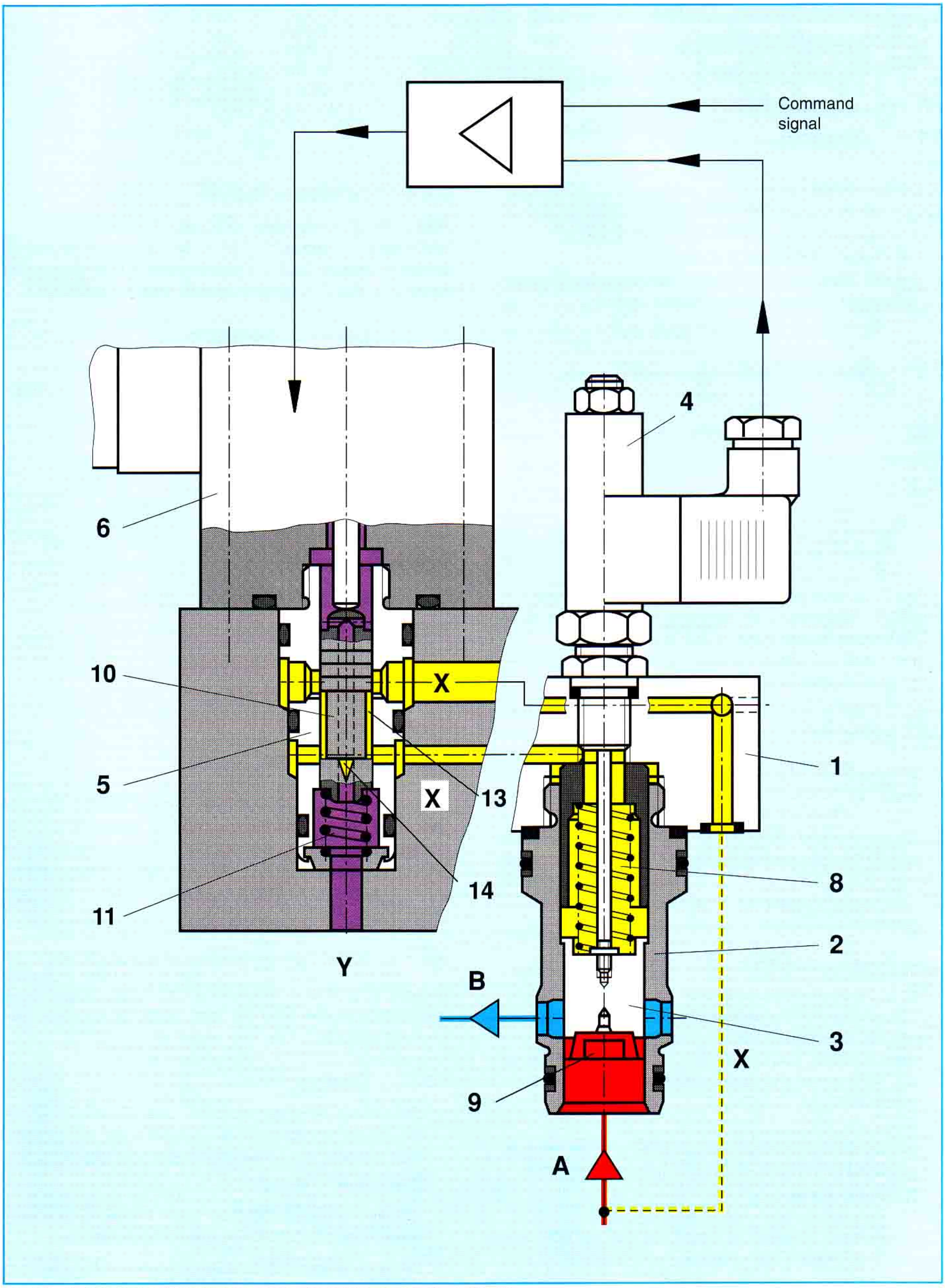


Fig. 62: *2-Way proportional throttle valve (cartridge valve) Type FE..C*

5 Installation, Commissioning and Maintenance of Hydraulic Proportional Valves

5.1 General

In addition to the notes below, advice given in the following publications should be observed to ensure correct operation:

- the manufacturer's data sheets and
- the VDI Specifications, Commissioning and Maintenance of Hydraulic Systems, VDI (3027)

5.2 Installation

5.2.1 Installation Instructions

Before the valve is mounted in the system, the valve type should be compared with the order data.

1 Cleanliness:
- of surrounding area and proportional valve when mounting the unit
- the tank must be sealed from external contamination
- prior to installation, pipes and the tank must be cleaned of dirt, scale, sand, metal chips etc.
- hot bent, or welded pipes must be subsequently pickled, flushed and lubricated
- only use fluff-free material or special paper for cleaning purposes

2 Sealing material such as hemp, putty or sealing tape must not be used.

3 To ensure high stiffness of the system, hose lines should not be used between the valve and actuator.

4 The piping system must be made up of seamless precision steel pipes in accordance with DIN 2391/C.

5 The connecting lines between the actuator and valve must be as short as possible;
We advise that the proportional valve is installed as near as possible to the actuator.
The mounting surface must have a surface finish of $R_{t\,max.} \leq 4$ µm and a degree of flatness of ≤ 0.01 mm/100 mm length.

6 The mounting screws must agree with the dimensions specified in the data sheet and tightened to the specified torque.

7 An oil bath air filter is recommended as the filter breather. Mesh width ≤ 60 µm.

5.2.2 Installation Position

Any position, preferably horizontal; however, if the proportional valve is mounted on an actuator, care should be taken to ensure that the valve spool is not positioned parallel to the acceleration direction of the actuator.

5.2.3 Electrical Connection

Refer to the relevant data sheet for electrical connection. Special protection classes require special measures which are stipulated on the relevant data sheet.

5.3 Commissioning

5.3.1 Fluids

Note recommendations given in data sheet.

Note pressure and temperature ranges.

Generally, the following can be used:

- mineral oil H-LP to DIN 51 525
- polyglycol in water solution
- phosphate-ester

Other fluids on request.

The maximum temperatures recommended by the manufacturer of the fluid should, if possible, not be exceeded in order to protect the pressure medium. To ensure constant response characteristics of the system, it is advisable to maintain the oil temperature constant (±5 °C).

5.3.2 Is the Correct Sealing Material Used?

When using HFD (phosphate ester) fluids, and also for high temperatures > 90 °C, viton seals (designation "V") must be used.

5.3.3 Filtering

- To ensure long service life, use 10 µm absolute pressure line filters for the proportional control, the filter element pore size specified in the data sheet can however also be used.
- The permissible pressure drop for pressure line filters must be greater than the operating pressure.
- We recommend filters equipped with a filter clogging indicator.

- Absolute cleanliness must be ensured during filter change. Contamination at the outlet side of the filter is flushed into the system and causes faults and malfunctions.
  Contamination at the inlet side reduces the service life of the filter element.

5.3.4 Operating Pressure for the Pilot Valve

The pilot pressure should not exceed 30 bar. If the pilot pressure exceeds 100 bar, a sandwhich plate pressure reducing valve must be installed on the inlet side.

Pressure peaks from the tank line can be avoided with a non-return valve.

5.3.5 Solenoid Venting

To ensure perfect operation, it is necessary to bleed the solenoid at the highest point of the valve during initial operation. Under certain installation conditions, the tank line must be prevented from running empty by the installation of a preload valve.

5.4 Maintenance

5.4.1 Return of Valve for Servicing

When returning a defective valve, it is necessary to protect the base surface of the valve from the effects of dirt.

Careful and adequate packing is advisable to ensure no further damage is incurred during transport.

5.5 Storage

Storage room requirements:

- dry, dust-free room, free of corrosive materials and vapours

For storage longer than 3 months:

- fill housing with preservative oil and seal.