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Hydrostatic Drives with Secondary Control Unit

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1 The basic principle of the control of the secondary unit

Hydrostatic drives which have been applied world-wide since 1980 under the general description of **load matching** or **secondary controls** are, due to their specific characteristics, much more comparable to electrical drives with closed loop control than to conventional hydraulic drives.

Secondary control is of interest wherever conventional drives can no longer fulfil the technical requirements regarding dynamic response, accuracy of speed regulation or positioning or wherever there is the opportunity of energy recovery without the need to convert this into other forms of energy.

In drive technology, two parameters are of importance to the power being transmitted:

- the torque M in Nm and
- the speed n in rpm.

These mechanical parameters correspond to the following parameters in hydrostatic drives:

- pressure p corresponds to torque M and
- flow Q in L/min corresponds to speed n.

Dependent upon the coupling of the mechanical and hydraulic parameters, two drive concepts can be defined:

- drive systems with flow coupling (conventional systems)
- drive systems with coupling via the operating pressure (systems with control of the secondary unit).

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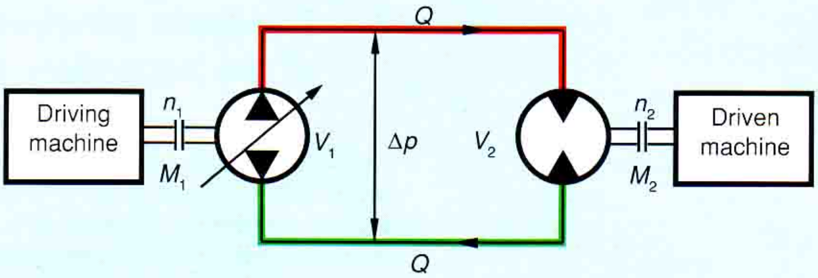
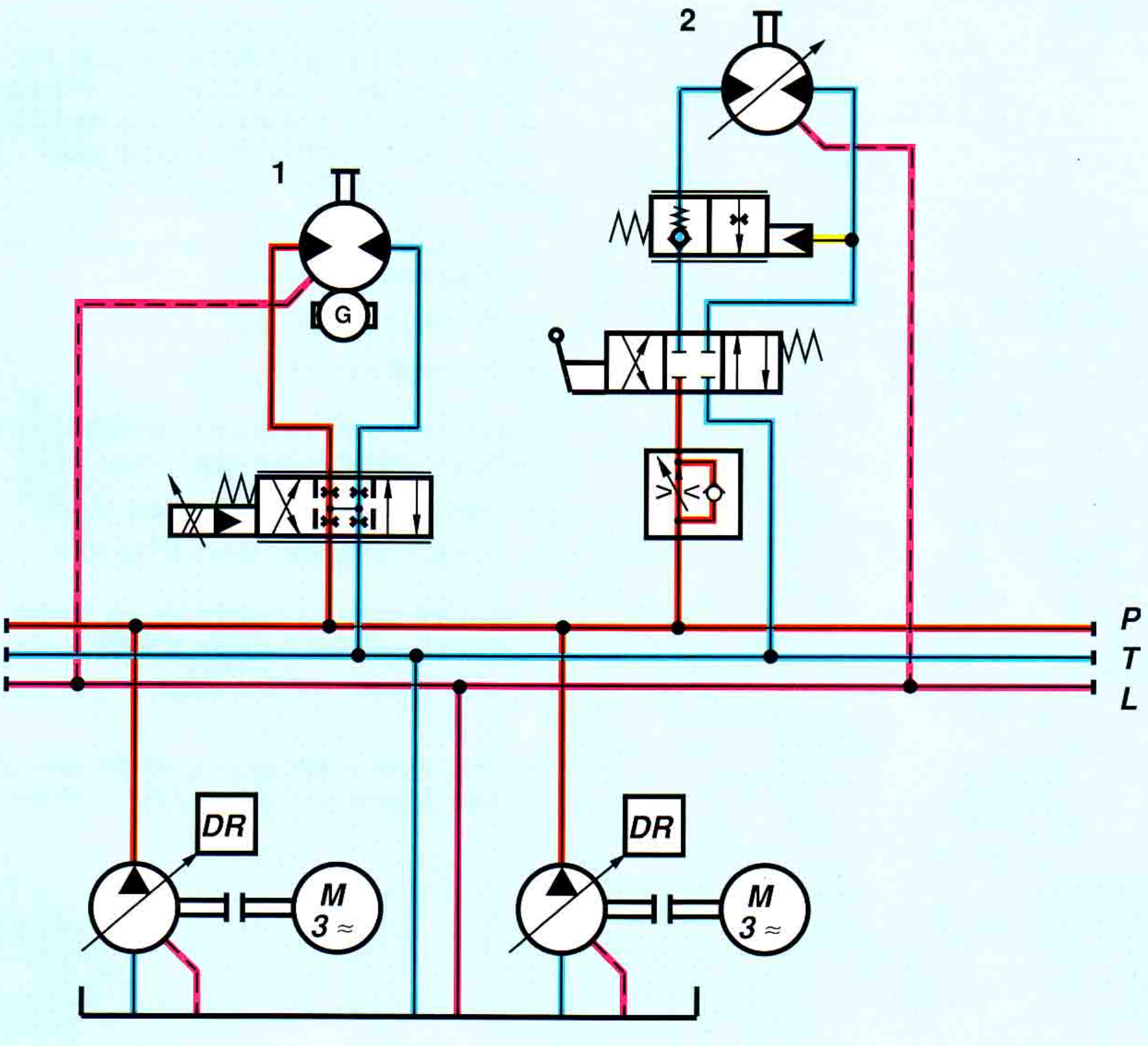
Drive Systems with Flow Coupling (conventional systems)

The conventional hydrostatic drive system works with flow coupling, i.e. the speed of the primary unit (pump) and the secondary unit (motor) are inter-related by virtue of the hydraulic flow Q in L/min. *Fig.1* (top) shows this relationship using a closed circuit drive.

The volumetric flow Q in L/min (which is determined by the input drive speed n_1 in rpm and the pump displacement V_1) causes the hydraulic motor to achieve an output speed n_2 dependent upon its displacement V_2.



Flow of power with superimposed flow coupling



Actuator on a central oil supply system

Fig.1: *Conventional hydrostatic drive*

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In heavy engineering and in ship building it is common practice to install hydraulic systems with a central oil supply on a so-called ring main system. These operate at a constant pressure using pressure regulated pumps and with many actuators and/or machines connected in parallel. In order to ensure that all of the fluid does not flow through the actuator with the lowest level of resistance, it is necessary to install throttling elements in the energy transmission lines. These ensure that the relevant amount of flow reaches the individual actuators. Thus, in order to obey the laws of flow coupling, the constant pressure system is converted into a constant flow system.

The illustration at the bottom of *Fig. 1* shows two actuators in open circuit. Actuator 1 is a fixed displacement motor with an electrical tacho-generator in a closed loop speed controlled drive. The control element can be either a proportional valve or a servo valve. Energy is supplied to the system by means of two pressure regulated pumps. Actuator 2 can be either a fixed displacement or a variable displacement motor. The maximum flow to this unit is limited by a flow control valve. Below this maximum flow the motor is controlled by means of a directional valve which can control both the direction of rotation and can throttle speed even further. If the output units tend to act as generators, i.e. when decelerating or lowering a load, energy is simply converted into heat in a counter balance valve.

In the throttling operations illustrated here, and under partially loaded conditions, a not inconsiderable proportion of the power is converted into heat losses. This is in fact the proportion of the pressure generated by the pump and not required by the actuator at any given flow.

The energy balance leaves much to be desired. The energy usage at the primary end is high.

With any change of torque required at the output end, the system responds with a change in pressure Δp. This causes the oil column to compress and then expand again. This has an adverse effect on the system stability due to the “hydraulic spring”. It is therefore often necessary in practice to damp the system by increasing the control time of the pump in order to bring the control of the pressure build-up and decay and system stability under control.

It was thus necessary to look for another drive concept which would not have these disadvantages and which would have the following characteristics:

- Parallel operation of a number of actuators without limitation.
- Energy transfer from the primary to the secondary units without throttling.
- Energy recovery for use by other actuators or by returning the energy to the primary unit, again without throttling.
- A constant operating pressure in order to eliminate the influence of the hydraulic spring.
- The ability to include accumulators within the system at any required point.
- Four quadrant operation.

These drive concepts can be illustrated as shown in *Fig. 2*. A pressure differential Δp is generated in a hydraulic system by the input of energy. The pressure level in the system is also determined by the loading condition of the accumulator. By means of isolating elements in hydraulic system, as many actuators as required can be connected to the ring main. There are no throttling elements in the energy carrying lines. When the actuators are working as motors, energy is drawn from the system. When they are operating as generators, energy is returned to the system. This energy which has been recovered may be used by other actuators or may be stored for later use or even returned to the energy supply unit and converted into another form of energy e.g. electrical energy. As the operating pressure or “hydraulic voltage” remains substantially constant, the influence of the hydraulic spring is no longer of importance, the dynamics of the system have free rein, the energy balance is improved and the primary energy usage is considerably reduced.

It only remains to find a technical solution which permits such a system to be controlled in every operating condition such that the influence of the actuator is also excluded from the system.

In this new system, we speak of **control of the secondary unit** or simply **secondary control.**

There are in fact three or four steps through which the previously un-informed reader must be taken to progress from *Fig. 3* to *Fig. 6* in order to make the introduction to secondary control easier. Once these four steps have been taken carefully, the basic principle of control of the secondary unit may be completely understood.

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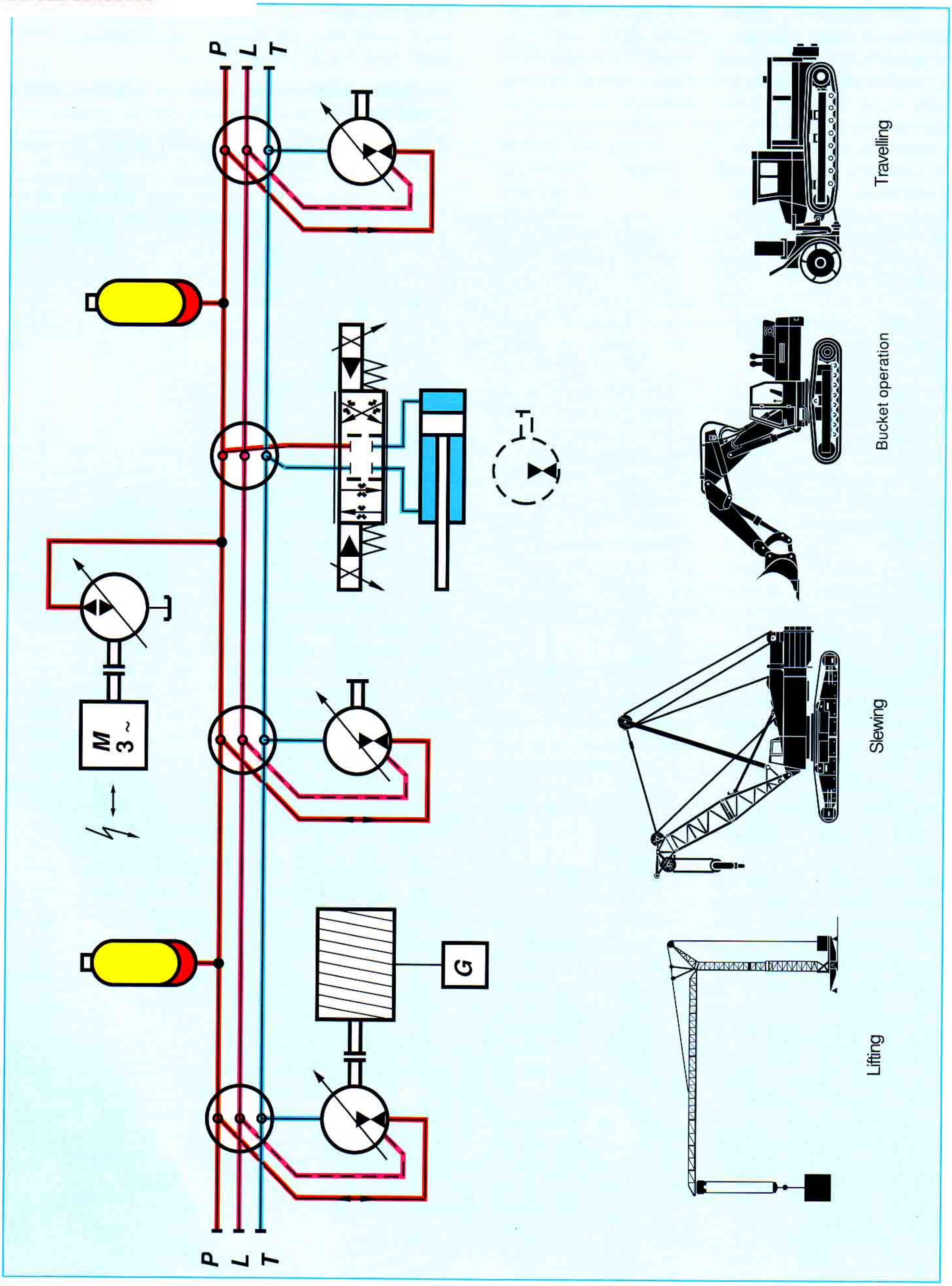

Fig.2: *Drive concept with some advantages over a conventional system.*

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1.2 Drive Systems with Pressure Coupling

1.2.1 Step 1 *(Fig. 3)*

For this, the following apply:

In a hydraulic system, a number of primary and secondary units are connected in parallel. They may work either as motors or generators. The operating pressure is held at a constant value. No throttling elements are fitted in the energy carrying lines. The hydraulic circuit can be either an open circuit *(Fig. 3)* or a closed circuit. The displacements of the hydrostatic units (either axial or radial piston units) —shown here as a winch drive— can be separately adjusted over the null point, i.e. both in value and direction, by means of a mechanical screw control with a hand wheel. The torque thus changes proportionally as follows:

$$Md \sim \Delta p \cdot V_g \sim \Delta p \cdot f(\alpha).$$

Δp	operating pressure in bar
V_g	displacement in cm^3
α	swivel in degrees.

If, after a load is applied to the winch, the hand wheel is turned experimentally backwards and forwards, it will be seen that the load rises and falls at differing speeds and it will not be difficult after a few tests to ascertain the balance point. In fact, this balance point is achieved when the mechanical torque due to load is exactly equal to the hydraulic torque which, at the constant operating pressure, is exclusively determined by the swivel angle of the unit.

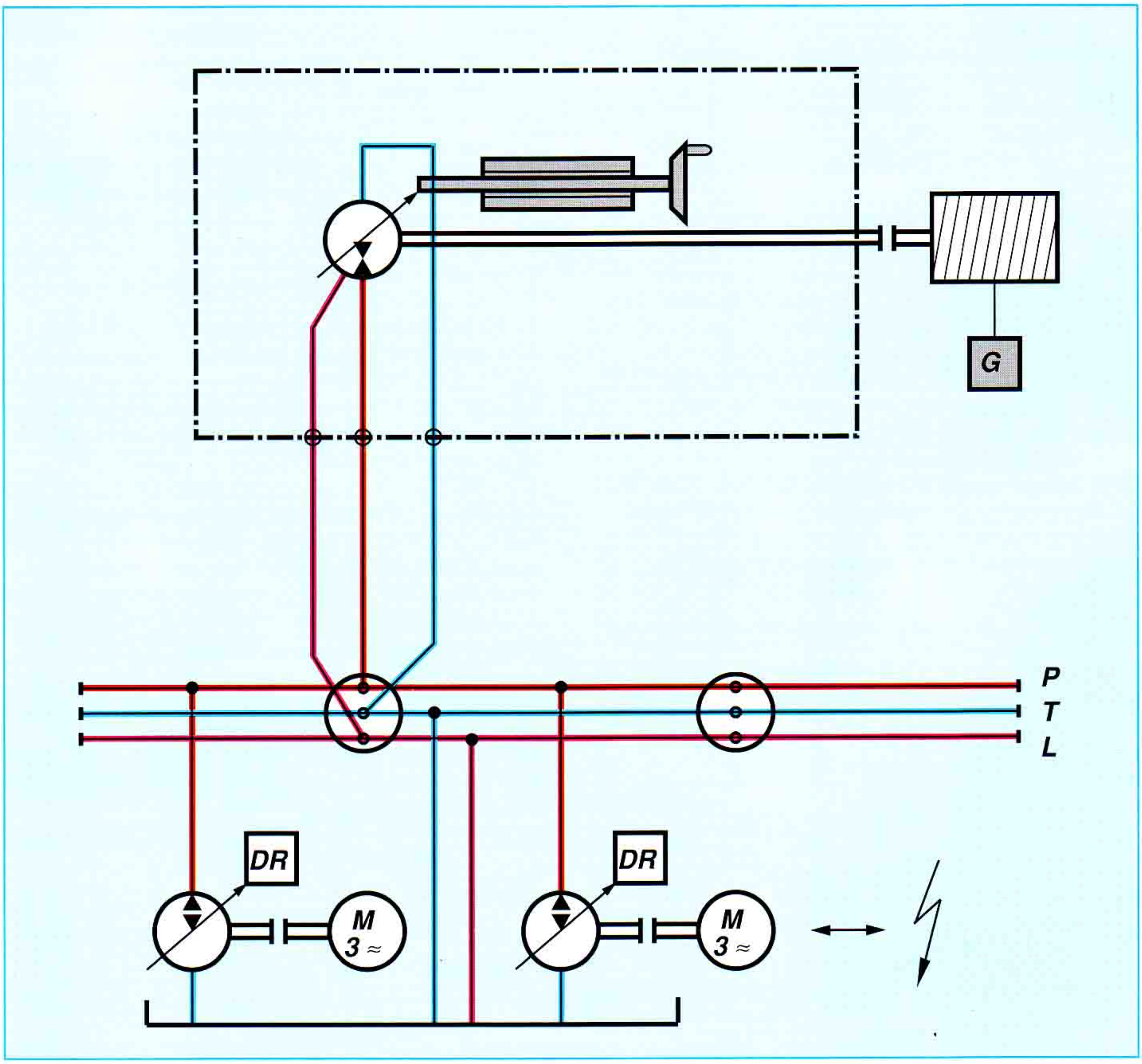

Fig.3: *Hydrostatic drive in a constant pressure system*

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In this condition no other forces are in operation. The load speed is zero and the load is held in position regardless of the volumetric efficiency of the unit and without the need to apply a mechanical brake. This characteristic is somewhat perplexing if one is accustomed to saying that a load cannot be held hydraulically. However, this statement refers solely to conventional hydraulic systems with flow coupling. In the case presented here, the volumetric efficiency has no effect on torque if the operating pressure remains constant.

If, moving from this stable condition, the swivel angle and therefore the displacement of the unit is increased by turning the hand wheel very slightly, the hydraulic torque becomes greater than the mechanical torque, the unit works as a motor and load will be raised slowly. The velocity increases with increasing swivel angle (torque) so that an exactly definable "hydraulic current" (flow) will be drawn from the system at a constant "voltage". Any increase in speed **and** torque therefore means that the flow requirement of the unit becomes greater.

We thus have the unusual relationship that a change in torque produces a similar change in flow. The analogy to closed loop electrical drives thus becomes clear.

If, starting once more at the balance point, the swivel angle is reduced, the mechanical torque exceeds the hydraulic torque. The unit then works as a generator, i.e. as a pump and the load falls. The potential energy is then fed back into the hydraulic ring main.

The direction in which the pressure is acting remains the same in this condition even though the direction of rotation has been reversed.

If the winch is to be lowered with an empty hook, the swivel angle must be reversed over zero into the negative area. This means that the unit must once more act as a motor as the load due to the empty hook is too small to cause the unit to act as a generator.

This first step has little in common with secondary control. It has been described only to show the possibility of achieving a throttle free drive of a number of units in parallel with pressure coupling via a constant operating pressure.

The overall characteristics of this drive system in which a torque is generated hydrostatically and the driven machine reacts with an appropriate speed is totally different to the requirements in practice. Normally, a preset speed is demanded of a hydrostatic drive. The latter then generates the required torque automatically via a closed loop system in order to be able to hold the speed constant under the operating pressure being applied at that time. In order to be able to operate such a system economically, technical alterations and additions must be made to the axial piston unit shown in *Fig. 3*.

1.2.2 Step 2 *(Fig. 4)*

The mechanical positioning device for the swivel angle has been replaced by a volume dependent positioning cylinder. As no statement about output speed n_2 can be made from the volumetric flow alone, the "lost" speed information must be determined in another way and fed to the positioning system as an overriding signal value. This determination of speed and the feedback of the signal into the positioning function is assumed in a hydraulic tachometer generator in the control circuit. This tachometer can act as either a pump or a motor. It feeds the positioning signal to the volume dependent cylinder and regulates its position, so that the speed of the secondary unit is reduced to zero and the required torque is built up.

An equilibrium position is once more achieved when the mechanical and hydraulic torques at the coupling point are the same. This is exactly the case when the differential pressure in the control circuit at the positioning cylinder and the tachometer are zero, i.e. when Δp_s equals zero.

If the loading on the winch drum is now changed, equilibrium is lost. The load starts to move and the winch drum turns. At the same time pilot oil from the tachometer is fed to the positioning cylinder so that its position is changed to suit the new torque levels. At the end of this adjustment, a new state of equilibrium is achieved.

Under conditions of constant load, the same process is repeated if the operating pressure were changed as would occur, for example, if other actuators drew power from the system and lowered the level of charge in the accumulator.

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In contrast to *Fig. 3*, additional accumulators have been included in *Fig. 4*. This has an influence upon the operating pressure dependent upon the loading conditions. We speak here of an imposed operating pressure, i.e. the pressure remains nominally constant. However, the pressure varies somewhat due to the amount of charge in the accumulators. This process has no influence upon the system characteristics. The circuit presets a speed of zero which is not dependent on the load or the operating pressure.

The load holding process is once more completely independent of the volumetric efficiency of the axial piston unit in the driving circuit but is not entirely independent of any leakage from the control circuit.

For example, leakage in the control circuit at the tachometer would lead to a corresponding creep speed of the winch drum.

In this way, we have constructed a torque control with speed feedback. The swivel angle of the unit and its displacement is a free value and is not uniquely defined. It changes with the required torque in order to maintain zero speed.

In order to be of use, a drive must be able to be operated. Further additions are therefore necessary.

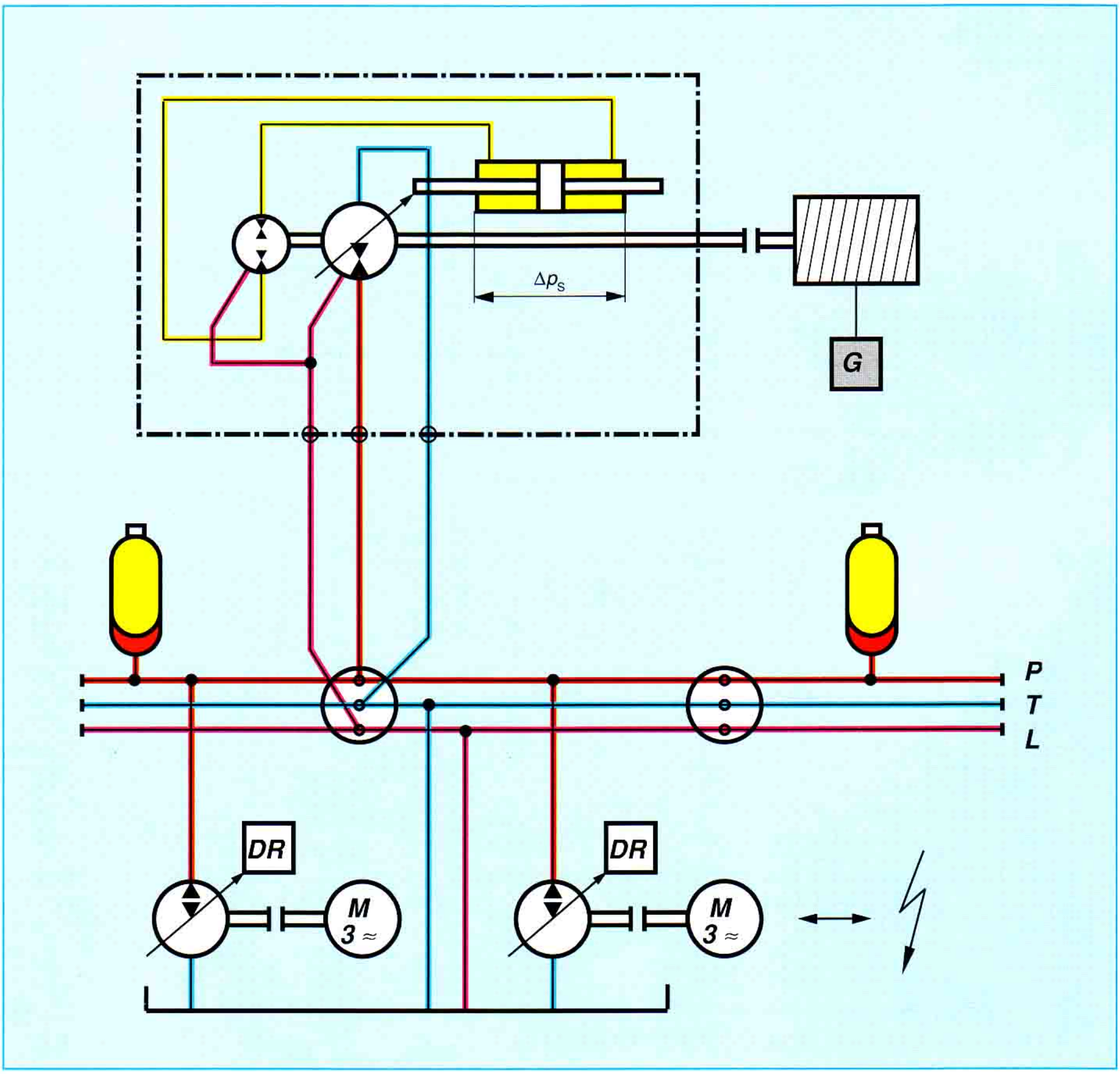

Fig.4: *System with control of the secondary units in a system with imposed pressure*

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1.2.3 Step 3 *(Fig. 5)*

As opposed to *Fig. 4*, a valve has now been added in the control circuit.

This valve can be either a proportional valve or a servo valve according to the dynamic response required. This valve is used to select the direction of rotation and to meter the required flow into the control circuit.

With the new pilot valve in the neutral position, the characteristics are the same as for *Fig. 3* and speed is zero. If a flow is now passed via the valve into the pilot circuit and the balance of Δp across the positioning cylinder is destroyed with pressure being built up at one side. The positioning cylinder then changes its position and thus alters the torque available at the secondary unit. An imbalance now occurs between the mechanical torque at the winch drum and the hydraulic torque available. The load starts to move and the drum turns. The pilot oil requirement of the tachometer rises proportionally to the rotational speed and the pressure difference is reduced at the positioning cylinder.

Equilibrium is once more achieved when the pressure difference at the positioning cylinder is reduced to zero. This occurs when all of the pilot oil flow is bled away via the tachometer.

The proportional flow control thus feeds a flow to the tachometer which acts as a command value and which is then taken as the command speed signal.

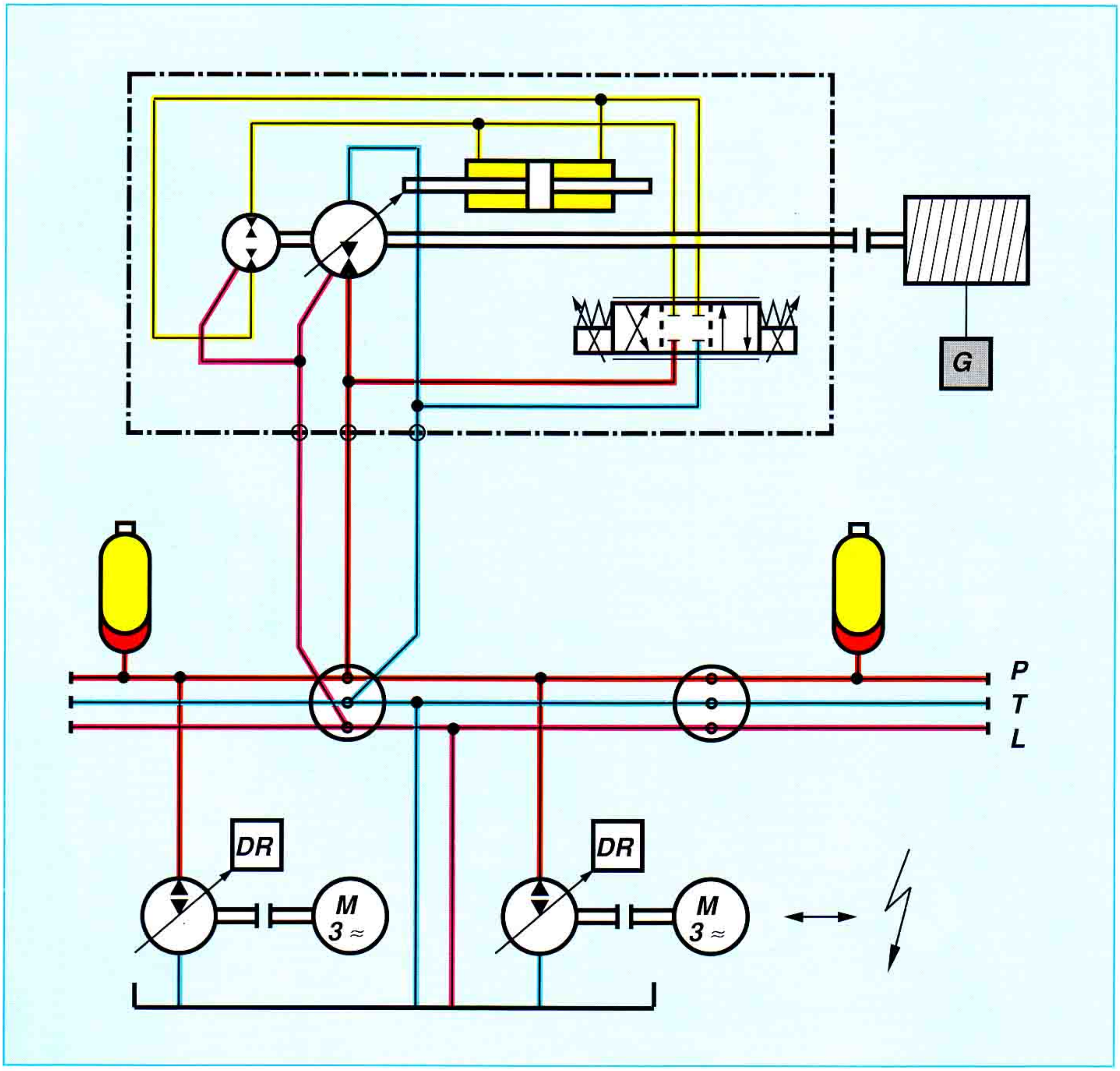

Fig.5: *System with control of the secondary units in a system with imposed pressure*

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This process is the secret of Secondary Control

In secondary control, we therefore have a speed control loop with the swivel angle or torque as a free value, i.e. the hydraulic unit seeks automatically to meet the preset speed input by automatically adjusting its torque in order to hold the preset speed dependent upon the available operating pressure.

A hydraulic tacho-generator is still used in certain special cases, e.g. in the fire or explosion hazard zones.

1.2.4 Step 4 *(Fig. 6)*

In the overwhelming majority of applications the hydraulic tacho-generator is replaced by an electrical tacho-generator capable of producing either analogue or digital signals. As leakage in the control circuit is also totally avoided in these cases, load holding may be achieved without difficulty.

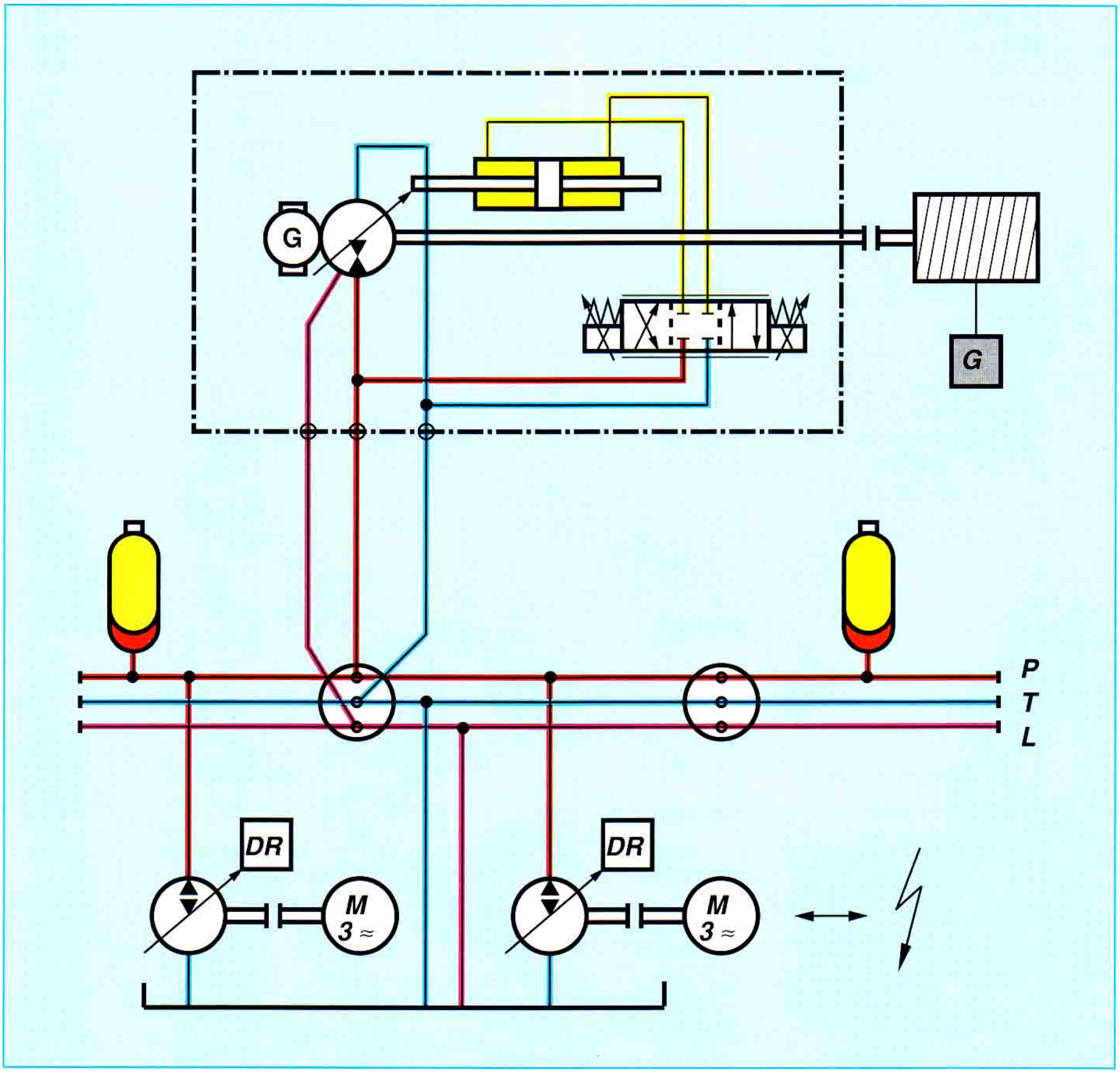

Fig.6: *System with control of the secondary units in a system with imposed pressure*

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1.3 Conclusions

In contrast to conventional drive systems, the swivel angle of the secondary unit is no longer co-related with an exactly defined drive speed n_2 in rpm. Instead, in a system with imposed pressure, it is defined by a definite torque M_2 in Nm.

When the system pressure changes, the swivel angle is so regulated as to maintain the required torque and the speed is held constant. In a system with secondary control almost loss free conversion of hydraulic energy into mechanical energy (motor operation) and of mechanical energy into hydraulic energy (pump operation) can be achieved. A four quadrant drive can be achieved in open circuit without problems. With the help of secondary control, in a similar manner to an electrical power line operating at constant voltage, as many independent actuators in most motor and generator operation can be coupled in parallel. The possibility of almost loss free energy storage by means of piston or bladder accumulators permits a new energy saving drive concept to be achieved on a universal basis.

2 Axial Piston machines for use in systems with Secondary Control

It would have worked against the introduction of secondary control had it been necessary to make more than minor modifications to the standard devices used in conventional systems. However, the increasing requirements placed upon this system technology in the course of time have required some design changes to be made. These have been mainly aimed at reducing the control time of the axial piston units and in the monitoring of operational reliability.

Fig. 7 shows a swashplate axial piston unit, series A4VS, equipped for use in a secondary control drive system.

The analogue or digital tacho-generator is driven through a zero backlash coupling from the second end of the drive shaft. A mechanical centrifugal switch is integrated into this unit. This gives an power cut-off signal should an over-speed occur. Operating on an inclined plane on the side of the positioning piston is an inductive positional transducer giving a direct electrical feedback of swivel

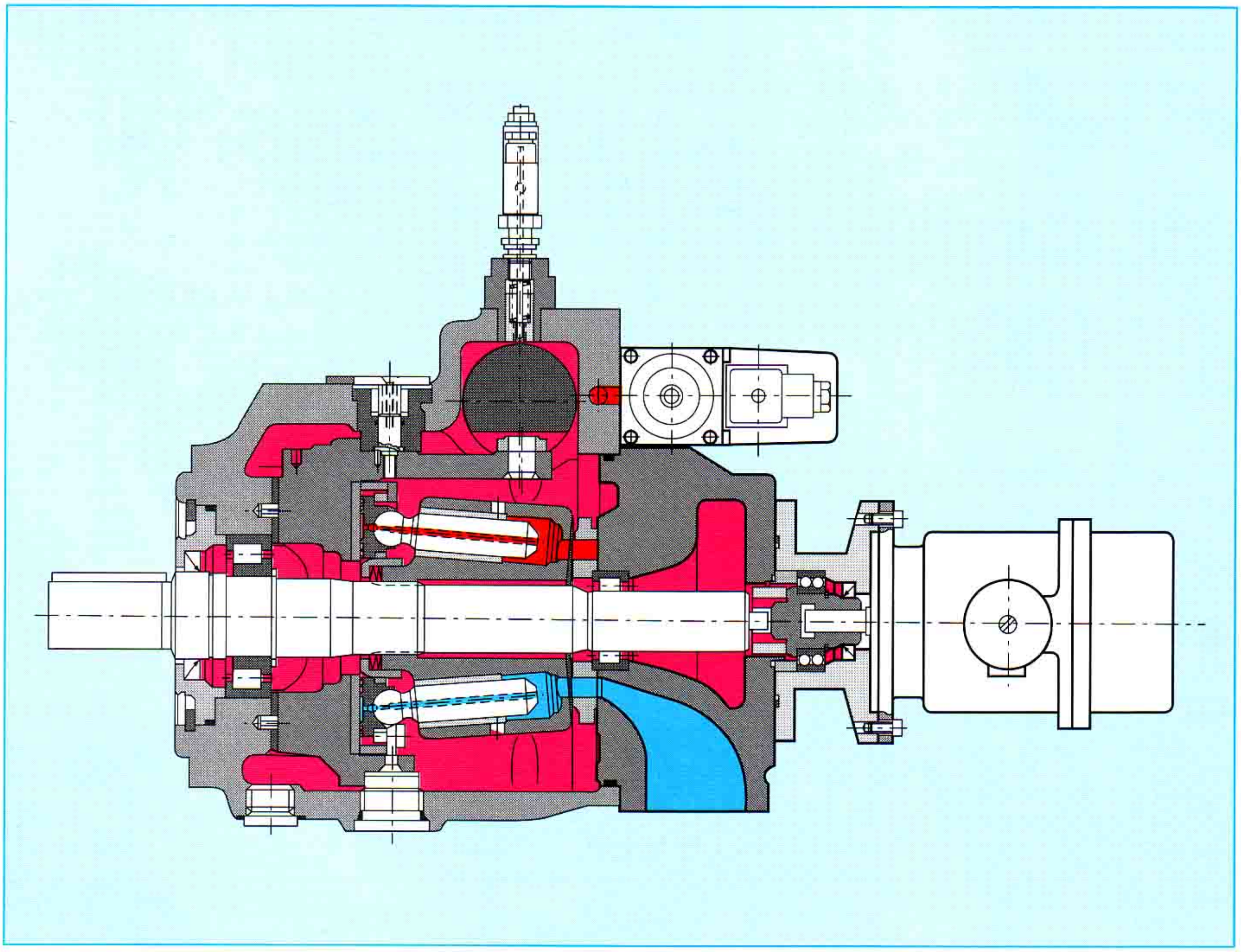

Fig.7: *Axial piston swashplate unit for secondary control*