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THE OPPORTUNITIES FOR GETTING ENERGY SAVINGS IN THE HYDROSTATIC DRIVE SYSTEM

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Abstract

Full picture of the energy losses in a hydrostatic drive system is a picture of the power of energy losses in the system elements. Paper presents the areas of the power fields of energy losses occurring in the elements of some hydraulic systems with different structures of the hydraulic motor speed control. Proposed graphical interpretation allows analysing and comparing different hydrostatic drive systems. In many constructed and manufactured machines currently used hydrostatic drive systems or electro hydrostatic systems of varying complexity. Today, the need for energy-efficient systems forces to some extent the development and improvement of computational methods using computer aided relating to energy efficiency systems. Hydrostatic systems especially in modern machines play a very important role. Actuators, such as hydraulic motors, hydraulic cylinders is commonly used for a long time, including on machines and equipment land and marine. Unawareness of proportions of the energy, volumetric, pressure and mechanical losses in elements is often the case. Problems connected with energy efficiency are essential for improvement of functionality and quality of hydrostatic drive systems, characterised by unquestioned advantages. Energy efficiency of hydrostatic transmissions, particularly those with throttling control of the motor speed, and also efficiency of the hydraulic servomechanism systems may be in fact higher than the values most often quoted in publications on the subject.

Keywords: *energy efficiency, energy losses, power, power of losses, hydrostatic system, control structures*

1. Introduction

If we accept the energy saving criterion for hydraulic systems with throttling control system, it is particularly important the possibility of using alternative solutions. One way to solve these problems in a system with constant capacity pump is the use an overflow controlled valve in a variable pressure system – p=var. Another solution is for example application in the system variable capacity pump cooperating with constant pressure regulator or Load Sensing regulator.

Graphical presentation, by fields of specified areas, of the power of energy losses in the hydrostatic drive and control system elements as well as power developed in the hydraulic displacement machines used in the system, becomes a tool facilitating comparing the values of particular losses. Presentation of the fields of power of energy losses allows making conclusions regarding e.g. elimination of the power of structural volumetric and pressure losses in the cylinder speed throttling control elements, in the proportional control systems and in the hydraulic servomechanism systems. Graphical interpretation by the field areas of the power of energy losses in the hydrostatic drive system elements and of the power developed by the system elements allows to compare those losses and powers with the area of the reference power field defined by the product $Q_{Pt}p_n$ of the theoretical pump capacity and the system nominal pressure [1, 2, 4, 6].

2. Hydraulic systems of the cylinder speed series throttling control fed by a constant capacity pump in constant and variable pressure conditions

The basic proportional control system is a system fed by the constant capacity pump. The overflow valve SP (Fig. 1) determines the system nominal pressure. The pressure decrease in the cylinder compensates the load on the cylinder. The proportional directional divider generates two pressure drops at the cylinder inlet and outlet. The pump in the p=const system must generate, before the overflow valve, pressure not lower than pressure required by the cylinder. Therefore, the hydraulic cylinder or the system-working cylinder may require pressure, depending on the load, in the range from zero to the nominal value. When the load approaches the nominal value, pressure decrease in the directional valve throttling slots tends to zero.

The mathematical description of losses and the energy efficiency of such a system are given in the work [4].

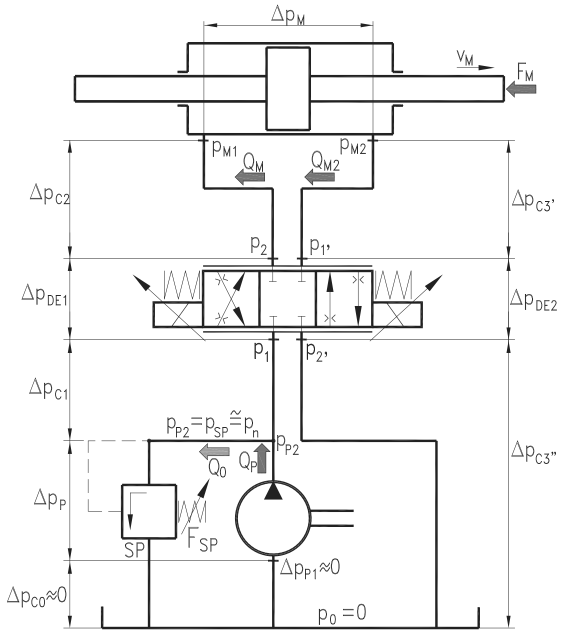

Fig. 1. System with proportional directional valve fed by a constant capacity pump with the use of an overflow valve – p=const structure

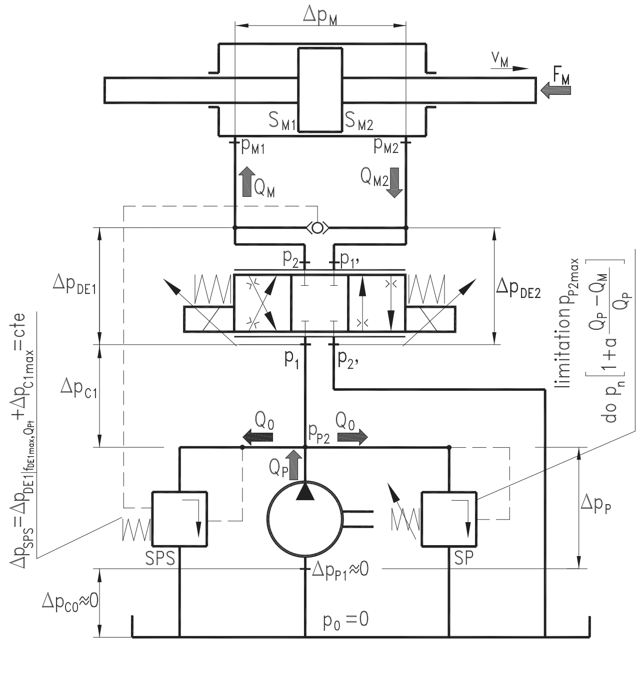

Fig. 2. System with proportional directional valve fed by a constant capacity pump with the use of a hydraulic cylinder supply conduit pressure controlled overflow valve – p=var structure

Energy savings can be achieved in a system of proportional divider powered pump with a constant capacity cooperating with an overflow valve controlled by the cylinder inlet pressure (Fig. 2). In this case, can severely reduce the structural volume losses and the structural pressure losses, can reduce mechanical and volumetric losses in the pump, and mechanical losses in the cylinder. The reduction of mechanical losses in the cylinder such a system results in a serious reduction of the pressure in the outlet of the cylinder [3-6].

The variable pressure (p=var) structure is represented by a system with constant capacity pump cooperating with an overflow valve controlled by the cylinder inlet pressure (Fig. 2). This is an advantageous solution from the viewpoint of the cylinder energy efficiency as well as of the pump and the whole control system efficiency. The variable pressure (p=var) structure with the overflow valve controlled by the current directional valve outflow to cylinder pressure allows to adjust the pump discharge conduit pressure to the current cylinder load, which limits the pressure loss in the working liquid outflow slot from the directional valve to the tank. Additionally, the system maintains constant piston speed irrespective of the load. This is an effect of maintaining practically constant pressure drop Δp_{DE1} in the proportional directional valve-throttling slot [3-7]. The mathematical description of losses and the energy efficiency of such a system are given in the works [3, 4].

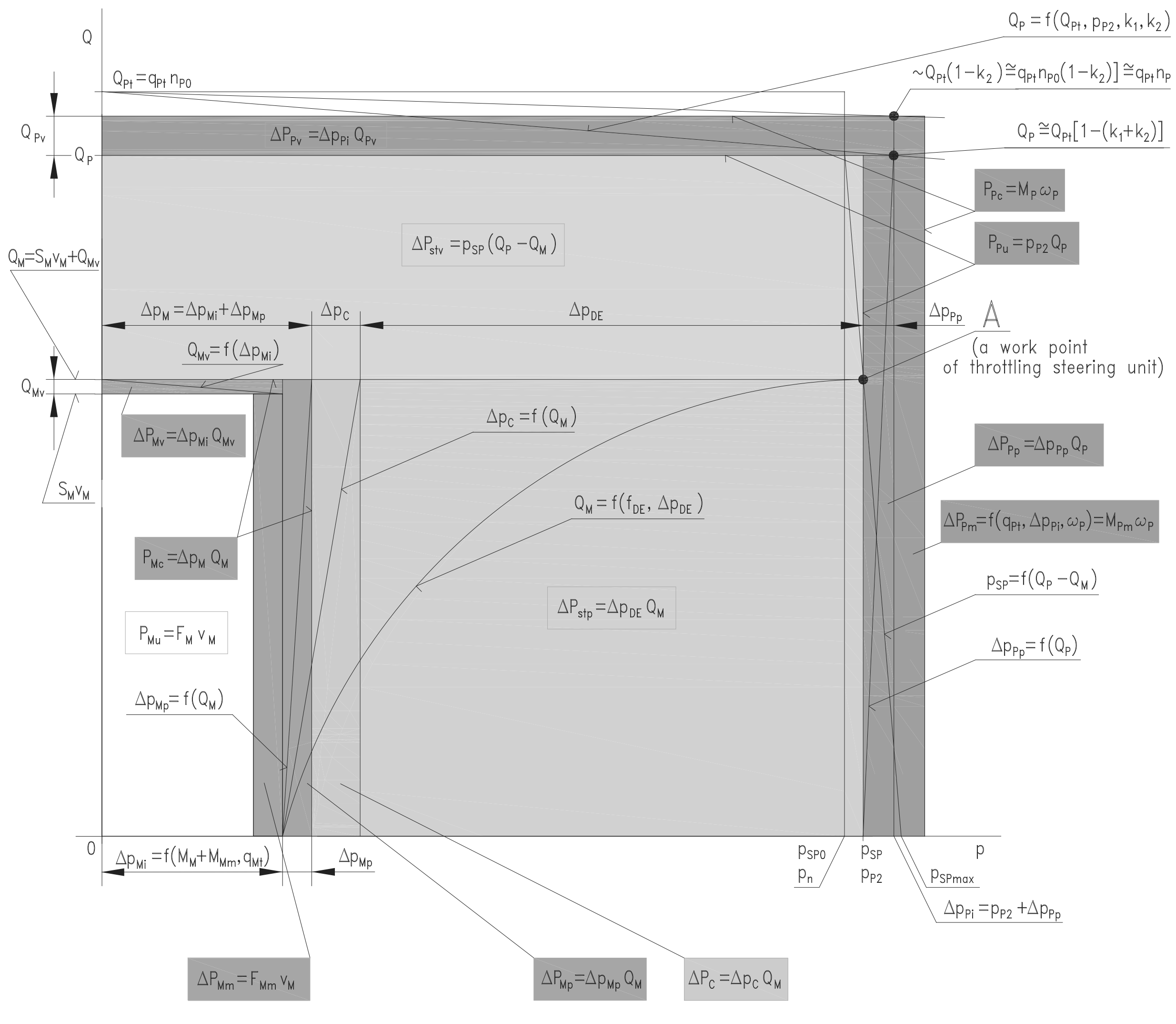

Fig. 3. Graphical interpretation of the power of losses in the hydrostatic drive and control system elements. An individual system with series throttling control of the hydraulic linear motor speed, fed by a constant capacity pump cooperating with the overflow valve in a constant pressure system – p=const

Figure 3 presents graphical interpretation of the power of energy losses in elements of an individual system with proportional control of a hydraulic cylinder, fed by a constant capacity pump cooperating with an overflow valve in a constant pressure system (p=const), and Fig. 4 – with an overflow valve controlled in a variable pressure system (p=var).

The pump operation nominal pressure p_n is determined by the need to ensure the hydraulic linear motor a maximum pressure drop Δp_{Mmax} to cope with the maximum force F_{Mmax} on the cylinder piston rod that may occur from time to time as an effect of the cylinder load.

The current cylinder useful power $P_{Mu} = F_M v_M$ is a product of the cylinder piston rod force F_M and the piston rod speed v_M. The hydraulic linear motor useful power P_{Mu} depends on the current load and is independent of the control structure and of the losses in the elements of a hydrostatic drive system with a specific structure.

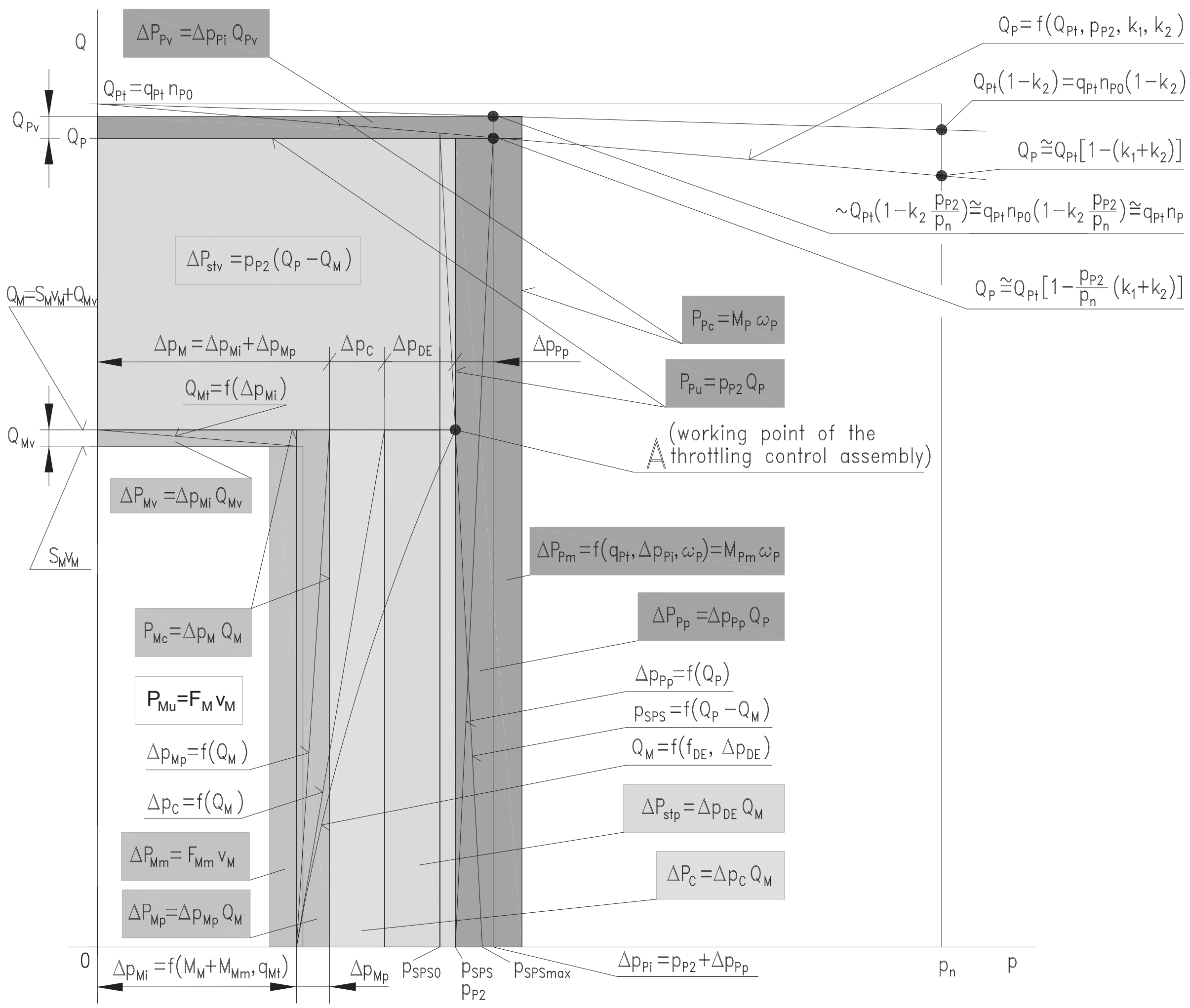

Fig. 4. Graphical interpretation of the power of losses in the hydrostatic drive and control system elements. An individual system with series throttling control of the hydraulic linear motor speed, fed by a constant capacity pump cooperating with the overflow valve in a variable pressure system – p=var

In Fig. 3 and 4 the hydraulic linear motor current useful power $P_{Mu} = F_M v_M$ is presented as the area of the white rectangle, to which the following fields are “added”:

– field $\Delta P_{Mm} = F_{Mm} v_M$ – of the power of mechanical losses in the cylinder,
– field $\Delta P_{Mv} = \Delta p_{Mi}$ — Q_{Mv} – of the power of volumetric losses in the cylinder,
– field $\Delta P_{Mp} = \Delta p_{Mp} Q_M$ – of the power of pressure losses in the cylinder,
– field $\Delta P_C = \Delta p_C Q_M$ – of the power of pressure losses in the system conduits,

– field $\Delta P_{stp} = \Delta p_{DE} Q_M$ – of the power of structural pressure losses in the throttling control assembly (in the proportional directional valve),
– field $\Delta P_{stv} = p_{SP} (Q_P - Q_M)$ – of the power of structural volumetric losses in the throttling control assembly (in the overflow valve),
– field $\Delta P_{Pm} = M_{Pm} \omega_P$ – of the power of mechanical losses in the pump,
– field $\Delta P_{Pv} = \Delta p_{Ppi} Q_{Pv}$ – of the power of volumetric losses in the pump,
– field $\Delta P_{Pp} = \Delta p_{Mp} Q_M$ – of the power of pressure losses in the pump.

The sum of areas of the cylinder current useful power P_{Mu} rectangle and the ΔP rectangles representing the values of power of particular losses occurring at a given instant in the hydrostatic drive and control system elements, makes up the area of rectangle corresponding to the current power P_{Pc} absorbed (consumed) by the pump from its driving electric motor and equal to the product of the current torque M_p and current pump shaft angular speed – $P_{Pc} = M_P \omega_P$.

The power P_{Pc} absorbed by the pump from the driving motor may be greater than the reference power $p_n Q_{Pt}$ – a product of the nominal pressure p_n and pump theoretical capacity Q_{Pt}.

3. Hydraulic systems of the cylinder speed series throttling control fed by a variable capacity pump cooperating with Load Sensing regulator in variable pressure conditions

There are another opportunities to reduce energy losses in the elements of the proportional control (pump, an unit with throttling control and hydraulic motor, especially linear cylinder), and thus the possibility of increasing the energy efficiency of the system with the valve throttling.

The use of a variable capacity pump equipped with Load Sensing control system with proportional control (Fig. 5) makes it possible to simultaneously eliminate structural volumetric losses, serious structural reduction of pressure losses, reduce mechanical losses in the linear hydraulic cylinder, and a reduction in mechanical losses and volume in the pump.

The use of a variable displacement pump equipped with a p = var regulator associated with the high cost of the pump and the regulator should take place after the economic analysis, that the additional investment costs compared with gains that can be achieved during operation of the device.

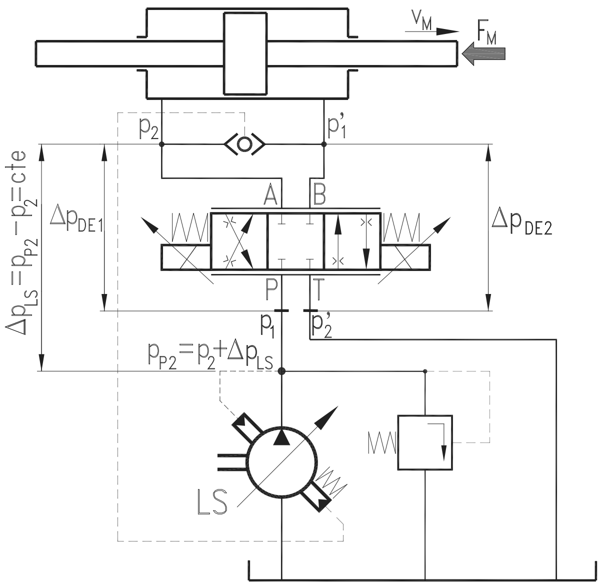

Fig. 5. Individual system with the linear cylinder speed series throttling control fed by a variable capacity pump cooperating with Load Sensing regulator in the variable pressure conditions p_{P2}=var; the throttling control assembly in the form of servo-valve or proportional directional valve

Figure 6 illustrates the fields of power of energy losses in elements of an individual system with the hydraulic linear motor – cylinder speed series throttling control, fed by a variable capacity pump cooperating with the Load Sensing regulator in a variable pressure p=var system. The series throttling control assembly may have a form of servo-valve or proportional directional valve (Fig. 5).

The use, as a supply source of the hydraulic cylinder speed series throttling control assembly, of a set consisting of a variable capacity pump cooperating with a Load Sensing (LS) regulator, totally eliminates the structural volumetric losses in a system. Power ΔP_{stv} of structural volumetric losses is equal to zero, because the current pump capacity Q_P is adjusted, by the LS regulator, to the current flow intensity Q_M set by the throttling assembly.

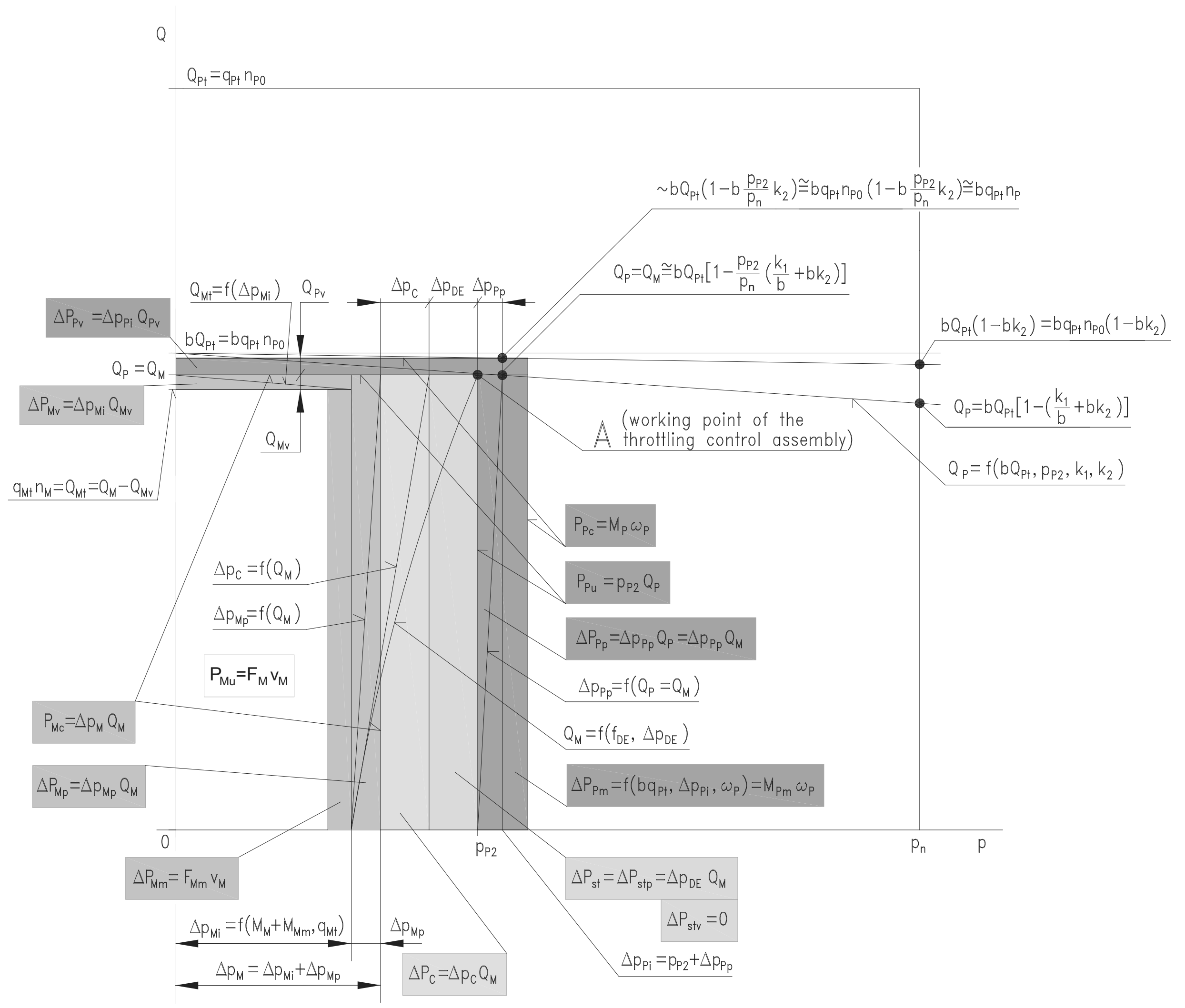

Fig. 6. Graphical interpretation of the power of losses in a hydrostatic drive and control system elements. Individual system with the hydraulic cylinder speed series throttling control fed by a variable capacity pump cooperating with Load Sensing regulator in the variable pressure system: p=var

The value $\Delta p_{LS}=p_{P2}-p_2$ of the pressure difference must allow to obtain, through the throttling proportional valve slot DE1 (controlling the flow intensity Q_M feeding the hydraulic linear motor), the flow intensity Q_M equal to DE1 slot area reaches then the maximum size f_{DE1max} and a possibility of pressure decrease $\Delta p_{LS}=\Delta p_{DE1}$ required by the throttling proportional design, with simultaneous capability of overcoming the conduit between the pump and the directional valve.

The current value of the pump discharge pressure p_{P2}, higher by a value of Δp_{LS} then the current pressure value p_2 at the throttling proportional directional valve outlet to the hydraulic linear motor, adjusts itself to the pressure value p_{M1} required by the cylinder at its inlet. The maximum limit pressure value p_{P2max} in the pump discharge conduit is determined by the overflow valve SP, whose opening pressure p_{SP0} is equal to the system nominal pressure p_n.

In the hydraulic cylinder speed series throttling control assembly Load Sensing feeding system, the power $\Delta P_{stp}=\Delta p_{DE}Q_M$ of structural pressure losses occurring in the throttling control assembly during loading the hydraulic cylinder with smaller load (force F_M) will be considerably reduced. With an elimination of the power ΔP_{stv} of the structural volumetric losses in the throttling control assembly, the LS system allows to decrease to a negligible value the sum of power ΔP_{st} of structural energy losses resulting from the use of series throttling as a form of precise hydraulic linear motor speed control.

The use, of a variable capacity pump with Load Sensing regulator reduces the sum of power of energy losses in the system to a value only slightly higher then the sum of power losses in elements of a system with volumetric control of the hydraulic linear motor speed (directly by a variable pump capacity). Power P_{Pc} absorbed by the pump from electric or internal combustion motor is slightly higher than the power P_{Pc} of a variable capacity pump directly driving the hydraulic linear motor.

4. Summary and conclusions

The hydrostatic drive energy efficiency is a product of the efficiencies of drive system components. Efficiency of the component elements is, in turn, a product of the mechanical, pressure and volumetric efficiency of those elements. While determining those efficiencies, the power of losses in the elements is not taken into account, but only torque or force of the mechanical losses, pressure losses in the conduits or intensity of the volumetric losses. It is acceptable in the case of rotational pumps, motors and double-piston rod cylinders. However, it is not sufficient in considering the energy efficiency of commonly used linear motors, single-piston rod cylinders and systems with those machines. Therefore, not always justified simplifying assumptions are applied [1-3].

Full picture of the energy losses in a hydrostatic drive system is a picture of the power of energy losses in the system elements. The system feeding pump shaft power is equal to the sum of the hydraulic motor shaft or piston rod power plus powers of losses occurring in the energy stream flowing through the component elements. Power delivered to the system on the pump shaft is also influenced by the interrelation between the pump driving motor speed $n_P = n_{Mn}$ and the pump shaft torque M_P. Powers of the energy losses in the system elements and also powers developed by the elements must be precisely defined. The picture of energy losses requires the range to be determined of the hydraulic motor useful power P_{Mu}, determined in turn by the range of torque M_M and angular speed ω_M of a rotational motor shaft, or force F_M and linear speed v_M of a linear motor. The picture of energy losses in a hydrostatic drive system should be built from the hydraulic rotational motor shaft or linear motor piston rod towards the system feeding pump shaft [1-3].

Paper illustrates the fields of power ΔP of energy losses in the individual system elements, where hydraulic linear motor speed control is effected by series throttling of the working medium flow in order to obtain the intensity Q_M corresponding to the linear v_M speed required by the cylinder driven device. The use of a throttling directional valve (proportional directional valve or servo valve) allows changing the cylinder speed precisely. A constant capacity pump, which is cheaper, may be used as a feeding device in the system with series throttling control, the pump cooperating with the overflow valve or controlled overflow valve, or else a variable capacity pump cooperating with the Load Sensing variable pressure regulator.

The change of structure from p=const to p=var, with the same system useful power P_{Mu}, brings in effect a serious decrease of the power ΔP_{st} of structural losses. Simultaneously, at the same cylinder speed v_M, in the p=var structure, the power ΔP_{Pv} of volumetric losses in the pump and power ΔP_{Pm} of mechanical losses in the pump decrease, but power ΔP_{Pp} of pressure losses in the pump slightly increases.

With small hydraulic cylinder speed v_M and small load F_M it can be noticed, that in spite of using a constant capacity pump, the power of structural pressure losses ΔP_{stp} and also power of structural volumetric losses ΔP_{stv} is considerably smaller in the p=var system compared with the p=const system. Although the intensity of flow Q_0 through the overflow valve to the tank with the same cylinder speed v_M is in the compared systems practically the same, the product of smaller pump discharge pressure p_{P2} and the flow intensity Q_0 (the Q_P-Q_M difference) results in a smaller value of the power ΔP_{stv} of structural volumetric losses in the p=var system.

With increasing the hydraulic cylinder speed v_M and load F_M to the maximum values v_{Mmax} and F_{Mmax} respectively, the power ΔP_{stv} of structural volumetric losses and power ΔP_{stp} of structural pressure losses, connected with the throttling control assembly, is minimized.

The greatest energy savings in the considered series throttling control system, compared with a series control system fed by a constant pressure constant capacity pump, are obtained during the hydraulic cylinder operation at small speed v_M.

The use, as a feeding source of the hydraulic cylinder series throttling speed control system, of a variable capacity pump with the Load Sensing regulator operating at a pressure $p_{P2}=\Delta p_{LS}+p_2\approx\Delta p_{LS}+p_{M1}$, slightly higher than the current pressure p_{M1} required by the hydraulic cylinder at its inlet slightly reduces the sum of power of energy losses in the system to a value only slightly higher than the sum of power of losses in the elements of a system with volumetric control of the cylinder speed (directly by a variable pump capacity). Power $P_{PC}=M_P\omega_P$ absorbed by the pump from the electric or internal combustion drive cylinder is only slightly higher than the power P_{Pc} of a variable capacity pump directly driving the hydraulic cylinder.

The considered LS system operates in the whole range $0\leq F_M\leq F_{Mmax}$ of the hydraulic cylinder load and in the whole range $0\leq v_M\leq v_{Mmax}$ of its speed with the energy efficiency η only slightly lower than the efficiency of a volumetric control system (directly by a variable capacity pump). The difference between overall efficiencies η of both systems will be inversely dependent on the capability of increase of the area of throttling proportional valve slot f_{DEmax}.

The compared systems may achieve, during operating with maximum load and maximum speed, the same maximum overall efficiency. The variable pressure system becomes then a constant pressure system and the working conditions of all shown systems are the same.

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