Energy Use in Hydraulic Drive Systems Equipped with Fixed Displacement Pumps

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Abstract: *Using hydraulic drives has begun a long time ago, but in the 20th century they witnessed an outstanding expansion. Penetration of such systems in the field of complex equipment requiring high forces and speeds, provided with pumping units of 5 ÷ 500 KW, has represented an outstanding progress of hydraulics technology. Rather great progress, still not enough, has been done to reduce energy losses during use of fixed displacement pump systems. This paper is only the first part of a larger material which explores the evolution of energy efficiency increase over time.*

Keywords: *hydraulic drives, fixed displacement pump, energy consumption, energy loss, energy efficiency*

1. Introduction

One of the most important technical and scientific activities of recent years is related to the proper management of energy use. It is difficult to understand why mankind has come to waste significant percentage of the amount of energy produced (tens of percents) for subjective reasons. In this line, it should be pointed out that none of mechanical, electrical, hydraulic or pneumatic drives has not aimed since the beginning at lining up the amount of energy involved spent in performing a work-cycle phase with the amount of energy required, usable (output) energy.

In the field of hydraulics things started from providing for each working phase the energy required, there being no real interest in analyzing the usage of extra power, which has not been used in certain work-cycle phases. Thus, fixed displacement pump hydraulic systems have been for long time enough and satisfying.

Starting from the idea that power consumption is a function of flow and pressure and since pressure in the system is given by load, technical and scientific efforts targeted methods of varying the flow rate delivered, and therefore we witnessed the occurrence of adjustable pumps. From this moment the evolution of pumping groups consisted of creating the best devices for pump adjustment, which shall seek to equalize energy (or power) consumption to usable (output) energy in every moment of performing the work cycle of the machine.

2. Power use when driving a single actuator (hydraulic cylinder)

We will analyze hereinafter a common situation, where a branch of the machine requires a single actuator which will be controlled by a single directional valve from a single fixed displacement pump.

From the beginning it is established that delivery rate will be constantly at maximum (rated flow) Qn, and pressure limited by a safety valve to $p_{max.}$

In Figure 1 operation of cylinder C is ensured by starting the pump P and selecting the circuit **1** or **2** by means of hydraulic directional valve D, whose positions are selected according to system requirement by using electromagnets E_1 and E_2.

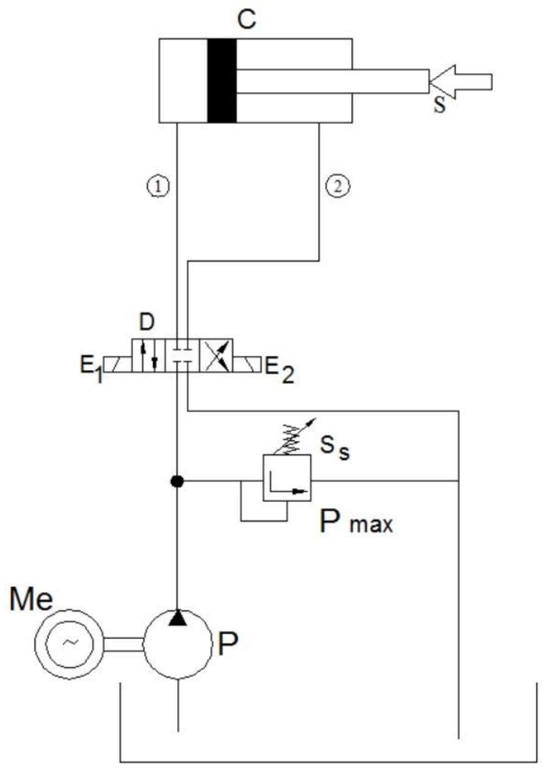

Fig. 1. Hydraulic diagram for driving a single actuator

For this simple configuration there can 4 working versions: a, b, c, d, assessed in the following lines depending on the pressure and flow requirements. For each of the working versions the next notations will be used:
N_u = usable (output) power;
N_e = excess power (power installed but unused);
N_p = lost power, converted into heat;
N_i = installed power.
Figure 2 graphically presents those 4 cases of energy (power) consumption.

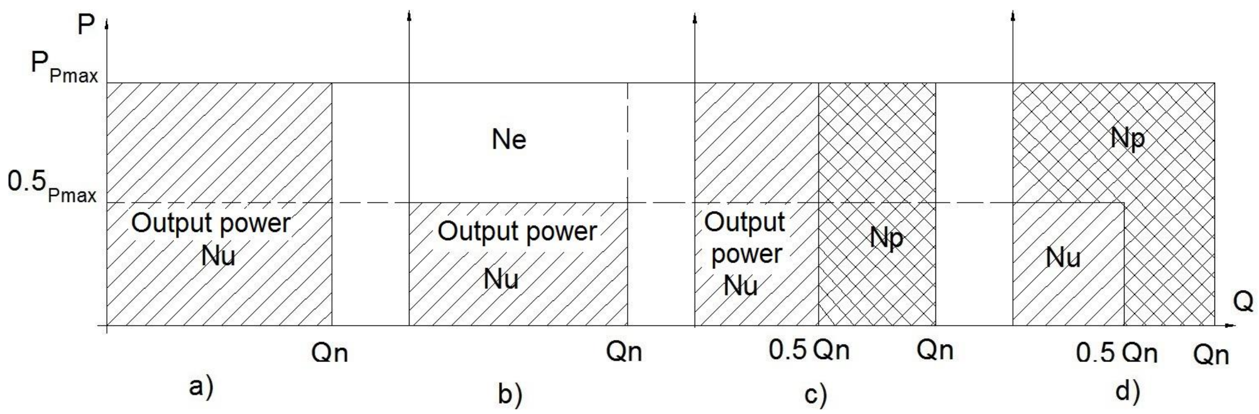

Fig. 2. Power graphs of energy consumption

a) The actuator needs all pump flow $Q_a = Q_n$ to achieve speed V_1.
To overcome load (S_a) pressure in actuator must reach the value $p_a = p_{max}$. In this case:

$$N_{ua} = \frac{p_a \cdot Q_a}{600\,\eta} = \frac{p_{max} \cdot Q_n}{600\,\eta} = N_c \quad (1)$$

b) The actuator needs all flow $Q_b = Q_n = Q_1$ to achieve speed V_1.
This time load (S_b) is smaller than load S_a.

$S_b = 0.5\ S_a$, hence it results that pressure p_b is: $p_b = 0.5\ \ p_a = 0.5\ p_{max}$

Since all the flow delivered by the pump is used, output power is:

$$N_{ub} = \frac{p_b \cdot Q_b}{600\ \eta} = \frac{0.5\ p_{max} \cdot Q_n}{600\ \eta} = 0.5\ N_c \tag{2}$$

The remaining power (0.5 N_c), although installed, is not used, and therefore $N_{eb} = 0.5\ N_c$, there being no losses and warming.
c) The actuator needs half of the flow $Q_c = 0.5\ Q_n$ to achieve speed V_c, and it must work at pressure value $p_c = p_{max}$ to be able to overcome load S_c.
In this case half of the pump flow will be discharged via general valve of the system, so lost power:

$$N_p = \frac{p_{max} \cdot 0.5\ Q_n}{600\ \eta} = 0.5\ N_C \tag{3}$$

The actuator needs half of the rated flow to achieve speed V_d, and it must work at half of the maximum pressure so that to be able to overcome load (S_d) $p_d = 0.5\ p_{max}$, and $Q_d = 0.5\ Q_n$.

In this case output power $N_{ud} = \frac{p_d \cdot Q_d}{600\ \eta} = \frac{0.5\ p_{max} \cdot 0.5\ Q_n}{600\ \eta} = 0.25\ N_c$ (4)

Mostly of energy is turned into heat.
$N_{pd} = 0.75\ N_c$

3. Power use in a hydraulic system with 2 actuators and 2 active phases

A hydraulic system which is common in industrial practice has the diagram showed in Figure 3. Analysis of energy loss is done for one phase only per each cylinder.

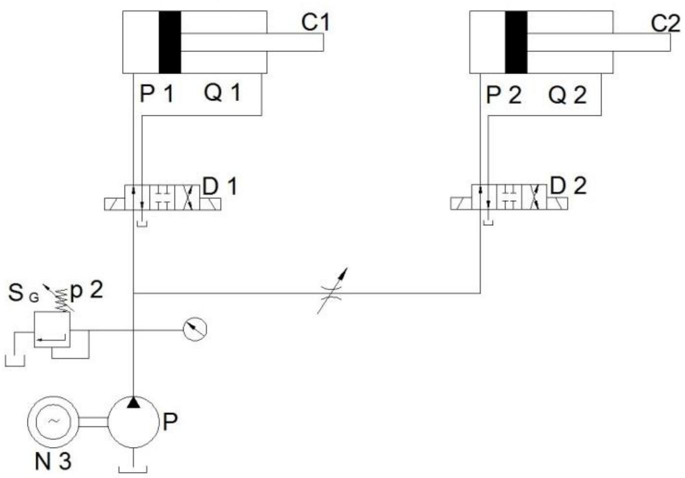

Fig. 3. Hydraulic diagram of a system with 2 actuators

In the first phase, pump flow is conveyed via directional valve D_1 to cylinder C_1 whose rod must overcome load S_1, and as a result pressure p_1 installs in the cylinder.
In the second phase, pump flow is conveyed via directional valve D_2 to cylinder C_2 whose rod must overcome load S_2, and as a result pressure p_2 installs in the cylinder.
Admitting that $p_2 = 3\ p_1$ and $Q_1 = 2\ Q_2$ it is roughly determined that $N_i = N_3 = \frac{p_2 \cdot Q_1}{600\ \eta}$, since the pump flow and valve control are constant, but at their maximum value.
In phase 2 usable power consumption is $N_2 = \frac{p_2 \cdot Q_2}{600\ \eta}$.

As one can see in the graph presented in Figure 4, usable power consumption for the 2 phases is NOT the same, but installed power N_i is the same.

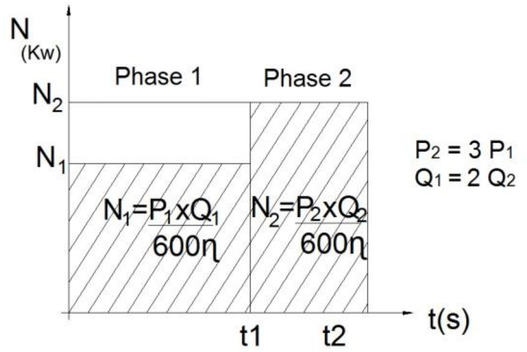

Fig. 4. Graph of usable powers consumption

Returning to the (rough) relationship - η includes all losses and yields –

$$N_2 = \frac{p_2 \cdot Q_1}{600\,\eta} = 2\ \frac{p_2 \cdot Q_2}{600\,\eta} = 2N_2 = 3\ = \frac{1 \cdot Q_1}{600\,\eta} = 3\,N_1, \tag{5}$$

if we relate to consumption utility, as one can also see in Figure 5, we obtain:

$$N_1 = \frac{N_3}{3};\qquad N_2 = \frac{N_3}{2};\qquad N_1 = \frac{2}{3}\,N_2 \tag{6}$$

It is very clear that power consumption is not at an optimum level in any of the phases, losses due to heating being extremely high.

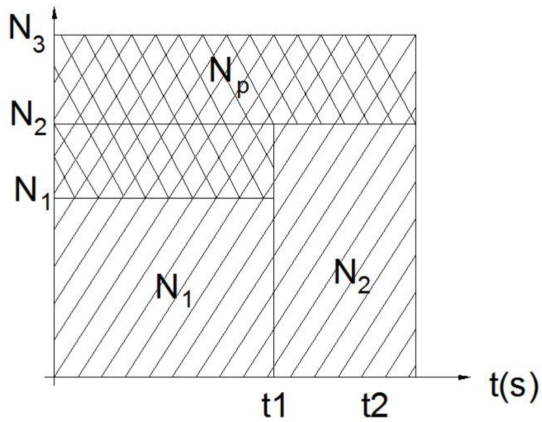

Fig. 5. Total energy consumption

4. Power use in systems in which each circuit has pressure control

To improve power use in circuits with two cylinders (Figure 3) it is possible to use the circuit in Figure 6, in which phases 1 and 2 are selected by directional valves D_1 and D_2 and controlled as to the pressure level by means of relief valves S_1 and S_2.
This simple modification of the diagram indicates lower power loss, even though the installed power is quite high. As one can see in Figure 7, excess power (power installed but unused) N_e increases in size at the expense of lost power N_p.

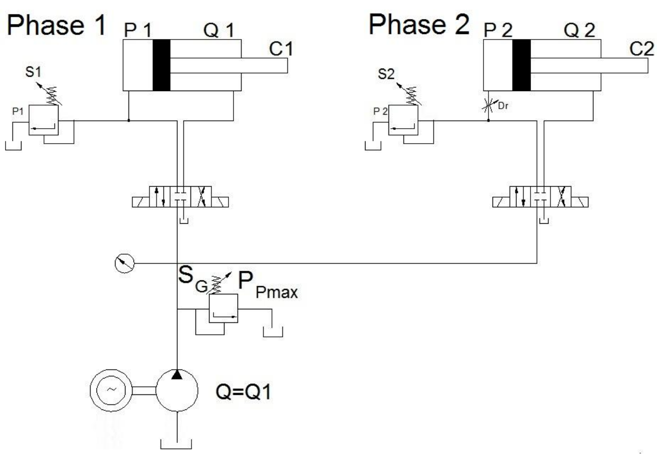

Fig. 6. Driving diagram with safety valves on each circuit

The graph in Figure 7 shows that in first phase in which all the flow $Q_1 = Q_n$ is used, but not at maximum pressure, only at a value $p_1 = \frac{1}{3}\, p_2$, a large portion of power remains unused (N_{e1}) and only a small portion is lost (N_{p1}).

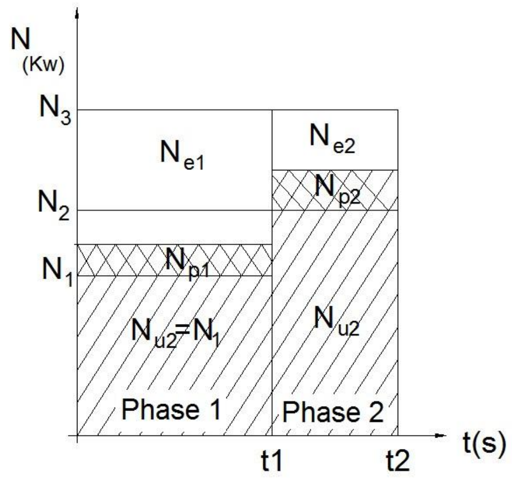

Fig. 7. Graph of level of the losses

In the second phase one can notice that losses are low; in this case as well a small portion of the installed power appears as unused power.
Nevertheless, the graph in Figure 6 shows better energy use compared to that shown in the graph in Figure 5.
Starting from the case in which: $p_2 = 3p_1$; $Q_1 + 2\,Q_2$ and $p_{max} \cong 1.25\, p_2$;

$$p_{max} = 1.25\, p_2 = 1.25 \cdot 3\ \ p_1 = 3.75\, p_1 \tag{7}$$

it results that installed power is:

$$N_i = N_3 = \frac{Q_1 \cdot p_{max}}{600\,\eta} \tag{8}$$

In phase 1

$$N_{u1} = \frac{p_1 \cdot Q_1}{600\,\eta} = \frac{2Q_2 \cdot 1/3 p_2}{600\,\eta} = \frac{2}{3}\,\frac{Q_2 \cdot P_2}{600\,\eta} = \frac{2}{3}\,N_{u2} \tag{9}$$

It can be noticed that much of the power is not used

$$N_{e1} = N_3 - N_{u1} - N_{p1}, \qquad (10)$$

and if we admit that $N_{p1} = 0$

$$N_{e1} = \frac{Q_1 \cdot p_{max}}{600\,\eta} - \frac{Q_1 \cdot p_1}{600\,\eta} = \frac{Q_1 \cdot 2.75\,p_1}{600\,\eta} = 2.75\ N_{u1} \qquad (11)$$

It turns out that there is a poor use of installed power, but at least with reduced energy losses.
In phase 2

$$N_{u2} \frac{Q_2 \cdot p_2}{600\,\eta} \qquad (12)$$

This time energy loss is:

$$N_{p2} = \frac{(Q_1 - Q_2)p_2}{600\,\eta} = \frac{Q_2 \cdot p_2}{600\,\eta} = N_{u2} \qquad (13)$$

and it is quite close to the loss in Figure 3.
By introducing this type of valve the losses in the first phase has been turned into unused energy, so with no consumption and no heating, although this power is installed.
Concluding:

$$N_3 = N_{u1} + N_{p1} + N_{e1} = N_{u2} + N_{p2} + N_{e2}. \qquad (14)$$

5. Using multiple pumps

5.1. Improving energy balance when using double pumps

One of the traditional solutions adopted to reduce energy losses in systems in which the phases are difficult to select is that with two coaxial pumps, as in the diagram in Figure 8.

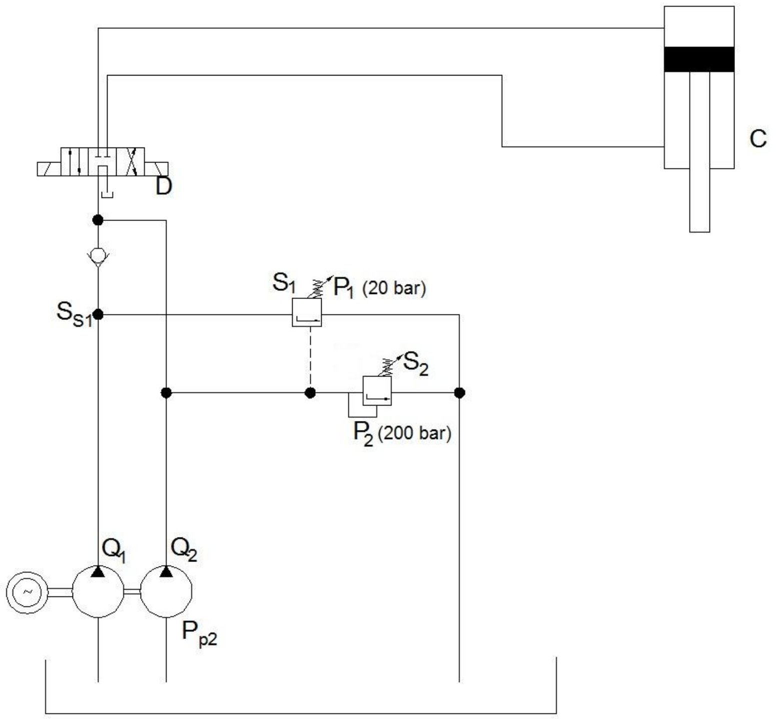

Fig. 8. Double pump hydraulic system

This solution is most often used in hydraulic systems of presses in which necessarily there are at least 3 standard phases.

The standard phases of the press are:

1. Rapid approach phase. Requires maximum flow and low pressure (Q_1; Q_2 and $p_1 \cong 0.1\, p_2$).
2. Full pressure phase. Requires low flow (for low speed) and maximum pressure ($Q_2 \cong 0.1\, Q_n$ and $p_2 = p_{max}$).
3. Rapid retract phase. Requires high flow and low pressure. Load is determined by the weight of the movable element plus friction forces.

Solving the problem with only one pump would lead to the situation in which in the second phase, the pressing phase, power losses would be as in Figure 2, C variant, where the flow lost through the valve would be approximately 90%.
By using the hydraulic system in Figure 8 with rough guide values set for each phase, energy losses look like in the graphs in Figure 9.

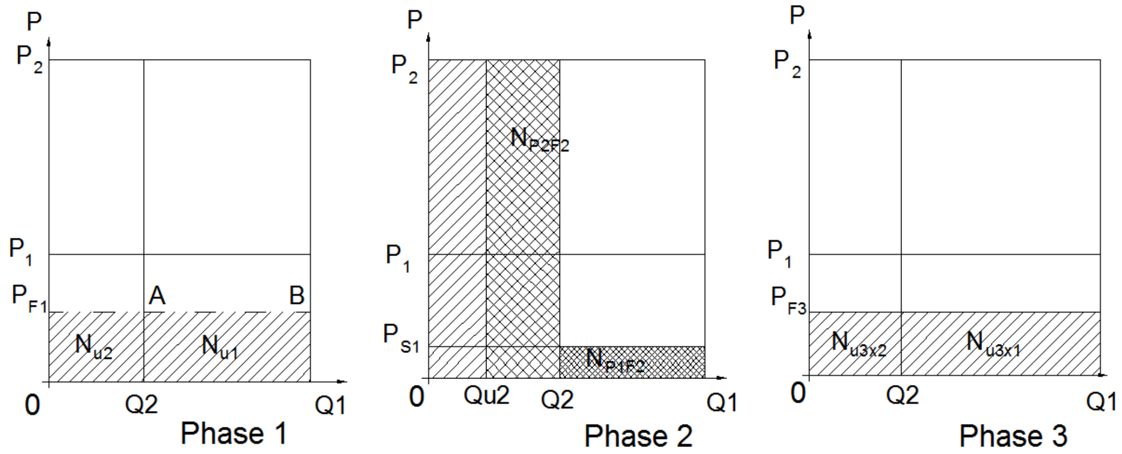

Fig. 9. Energy consumption at double pump systems

● **In phase 1** – Output power – $N_{uF1} = N_{u1} + N_{u2} = \frac{p_{F1} \cdot Q_{F1}}{600\,\eta}$ (15)

$Q_{F1} = Q_1 + Q_2$, and the pressure is established by the load and it s $p_{F1} < p_1 < p_2$

Power consumption $N_{cF1} \cong N_{uF1}$

N_{u1} – it is represented by the rectangle O – p_{F1} – B – Q_1, and

N_{u2} – it is represented by the rectangle O – p_{F1} – A – Q_2

● **In phase 2** – as a result of pressure increase in the system above p_1, valve S_1 opens and check valve S_{S1} is locked; thus, the whole flow Q_1 goes to the tank at minimum pressure set by valve S_1 (p_{S1}). This lost power has the value $N_{p1F2} = \frac{Q_1 \cdot p_{S1}}{600\,\eta}$, (16)

where p_{S1} is about 3 ÷ 6 bar, hence $p_{S1} < p_1$.
In this phase it is possible that part of the flow Q_2 is also discharged through pressure valve S_2 at pressure p_2, and only Q_{u2} is used.

$$N_{p2F2} = \frac{KQ_2 \cdot p_2}{600\,\eta}, \quad (17)$$

where K < 1 depending on the working speed in phase 2.

$$N_{pF2} = N_{p1F2} + N_{p2F2} \cong N_{p2F2} \quad (18)$$

$$N_{u2} = \frac{p_2 \cdot Q_{u2}}{600\,\eta} \quad (19)$$

● **In phase 3** –rapid retract phase- the whole pump flow p_{p1} is used at pressure resulting from weight and friction. Pressure is established on the circuits of both pumps.

5.2. Improving energy balance when using triple pumps or 3 coaxial pumps

Hydraulic systems which used pumping units with 3 coaxial pumps (Figure 10) or 3 pumps driven by independent electric (or heat) motor were actually the first steps towards digital hydraulics. Each pump has its own flow (Q_1, Q_2, Q_3) of which we can select for the system one, two or even all three, getting the flow rates Q_1; Q_2; Q_3; $Q_1 + Q_2$; $Q_1 + Q_3$; $Q_2 + Q_3$ or $Q_1 + Q_2 + Q_3$.

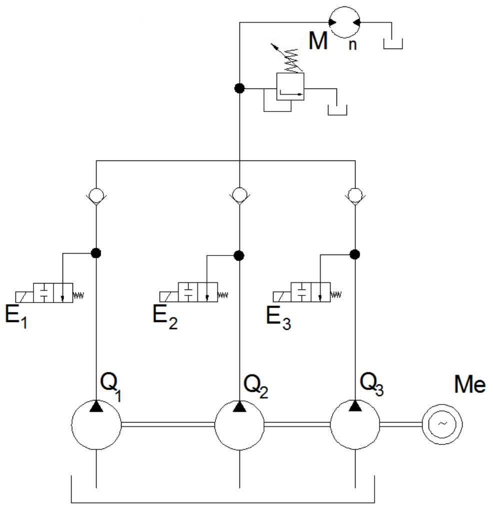

Fig. 10. Hydraulic system with 3 fixed displacement pumps

Using the electric automation system there is selected one of the seven variants of flow, which can provide one of the seven different speeds for the hydraulic motor M.

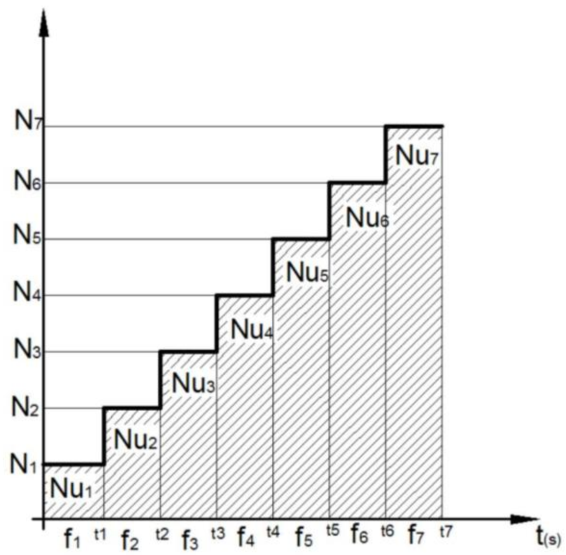

Fig. 11. Graph of installed power use

Output power is:

$$N_i \cong \frac{p_S \cdot (Q_1 + Q_2 + Q_3)}{600\,\eta}, \tag{20}$$

where $Q_2 = 2Q_1$; $Q_3 = 4Q_1$

Depending on flow requirements, one or more pumps will be selected.

$$N_{u1} = \frac{P_S \cdot Q_1}{600\eta} \quad (21)$$

$$N_{u2} = \frac{P_S \cdot Q_2}{600\eta} = \ 2 \ = \frac{P_S \cdot Q_1}{600\eta} = 2\ N_{u1} \quad (22)$$

$$N_{u3} = \frac{P_S\,(Q_1+Q_2)}{600\eta} = \ 3 \ \frac{P_S \cdot Q_1}{600\eta} = 3\ N_{u1} \quad (22)$$

$$N_{u4} = \frac{P_S \cdot Q_3}{600\eta} = \ 4 \ = \frac{P_S \cdot Q_1}{600\eta} = 4\ N_{u1} \quad (23)$$

$$N_{u5} = \frac{P_S\,(Q_1+Q_3)}{600\eta} = \ 5 \ \frac{P_S \cdot Q_1}{600\eta} = 5\ N_{u1} \quad (24)$$

$$N_{u6} = \frac{P_S\,(Q_2+Q_3)}{600\eta} = \ 6 \ \frac{P_S \cdot Q_1}{600\eta} = 6\ N_{u1} \quad (25)$$

$$N_{u6} = \frac{P_S\,(Q_2+Q_3)}{600\eta} = \ 6 \ \frac{P_S \cdot Q_1}{600\eta} = 6\ N_{u1} \quad (26)$$

$$N_{u7} = \frac{P_S\,(Q_1+Q_2+Q_3)}{600\eta} = \ 7 \ \frac{P_S \cdot Q_1}{600\eta} = 7\ N_{u1} \quad (27)$$

For each of the seven phases, besides output power Nu there is also power installed in excess, that will not be consumed; there will be lost only the part of this power which ensures oil recirculation through the pumps that are not actively involved in that particular phase, plus normal losses caused by operation of the pumping system. The amount of power that is lost is small compared to the amount of useful power consumption. The great advantage of this solution is that besides economical use of power the system allows simple automation, flow accuracy up to 12.5% and also functional structure quite simple and inexpensive.

6. Conclusions

This material only refers to fixed displacement pump hydraulic systems, and it highlights certain aspects such as:

- Although fixed displacement pump hydraulic systems have wasteful behaviour in terms of energy, there are a lot of cases in which they can be kept within reasonable limits;
- Complex high power systems lead to extremely significant energy losses, and therefore hydraulics technology has made considerable progress by using adjustable pumps and, more recently, by using Load Sensing and digital hydraulics.

Acknowledgment

This paper has been developed in INOE 2000-IHP, with financial support of ANCSI, under the Research Programme *–NUCLEU 2016,* project title: *Physics of processes for reducing energy losses and developing renewable energy resources by use of high-performance equipment,* project no. PN 16.40.03.01, financial agreement no. 5N/2016.

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