SIMULATION OF A ELECTROHYDRAULIC LOAD-SENSING SYSTEM WITH AC MOTOR AND FREQUENCY CHANGER

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There is an effective trend using input energy of dynamic systems nowadays. It is the same in the branch design and control of electrohydraulic systems. We try to develop systems characterised by high efficiency coefficients.
Standard electrohydraulic systems are characterised by low efficiency. A pump produces oil characterised by constant pressure and constant flow. As a result of this is energy wasted by stranglehold and by the pressure issue of the system. There are systems characterised by a higher coefficient of efficiency. The systems with constant pressure, which has better results and the Load-Sensing systems. The Load-Sensing system is the best, because the wastes by stranglehold and by the pressure issue system are minimal. There are more ways, how to realise such a load-sensing system, but the start point is the same. The flow is given by multiplication of speed and volume. So, if we want to change flow, we can do it by changing volume or speed of the pump. The first way is hydraulic load-sensing system and second one is electrohydraulic Load-Sensing (there is also third method – to change both of them).
I am interested in the electrohydraulic load sensing system. In my way it consist of an asynchronous motor controlled by a frequency changer and a pump with constant volume. I assume, this concept is very useful, because it consists of parts with uncomplicated structure, which means no problems during work.
The main part of my paper goes in the electrohydraulic Load-Sensing system. The scheme of this system is presented and itemised. There are presented models of items and solution of control circuits in the paper as well as the result of the simulation.

Keywords: Load-Sensing system, Frequency changer, Asynchronous motor, Hydraulic system

1 INTRODUCTION

Nowadays engineers have focus on effective using of input energy by dynamic systems. It is same as if we are interested in design and control of electrohydraulic systems. We try to develop systems, which are characterised by high efficiency coefficients. Even though there are more ways, how to do it, all of them starts at the same point – the standard hydraulic system.

These standard systems are characterised by constant flow and low efficiency coefficients. The flow can be calculated in easy way (1) and depends on angular velocity, volume and efficiency of the pump.

$$Q_{\max} = V_0 * n * h_{QHG} \tag{1}$$

Already in history a research of new concepts of the hydraulic systems has started. The results have been usually based on a pump characterised by changeable volume, which allows us to change the flow and it means increase the efficiency. Change of the volume is enabled by special construction of the pump. Usually it is fluent change of centring or stroke of the piston.

Other way, how to increase the efficiency is to use a pump characterised by constant volume and changeable speed of the pump. In this case is useful to use combination of asynchronous motor and frequency changer. This is smart and easy solution, because the frequency changer allows us comfortable control of the speed as well as reduces absorbed power.

2 THE ENERGETIC CHARACTERISTIC OF THE HYDRAULIC DRIVE

The pressure energy, which is used by hydraulic systems, is obtained by changing different form of energy, usually the electrical energy. If we want to make energetic evaluation of the hydraulic system, we have to criticise not only the consumer, but the pressure source too. This means, if we want to increase the efficiency of the hydraulic circuit, we have to modify the consumer, as well as the pressure source.

Energy produced by the pressure source is characterised by flow and by pressure of the system (2). Energy used by the consumer is characterised by similar way (3). The difference is wasted energy. One part of this wasted energy is wasted by exceeding of the local resistance, like the strangling and the second part is wasted by pressure issue of the system.

$$P_{HG} = Q_{HG} \cdot p_S \tag{2}$$

$$P_{HM} = Q \cdot p_l \tag{3}$$

Let us consider the basic concepts of the hydraulic circuits. They are shown at the table 1.

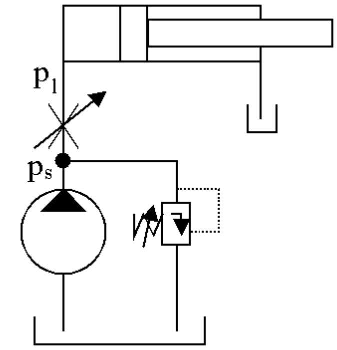
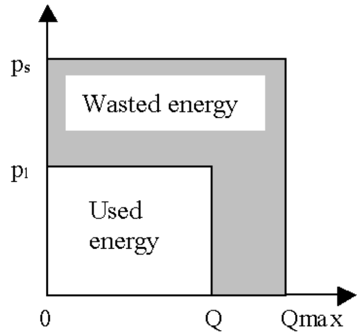
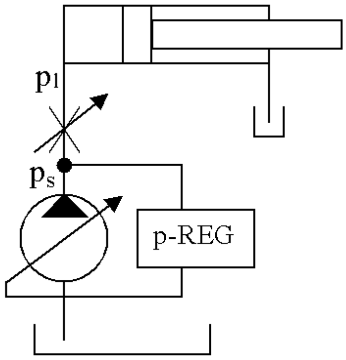
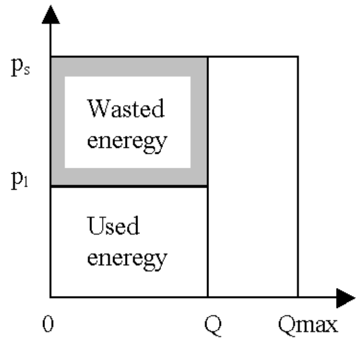
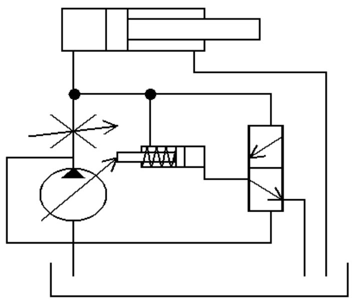
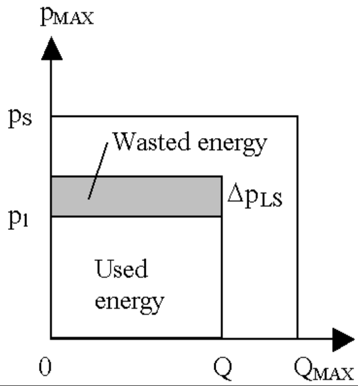
Hydraylic circuit	Scheme	The energetic characteristic
System characterised by constant flow $P_{HG} = Q_{\max} \cdot p_s$ $P_s = Q \cdot p_l$ $P_w = Q_{\max} \cdot p_s - Q \cdot p_l$ $h = 38\%$		
System characterised by constant pressure $P_{HG} = Q \cdot p_s$ $P_s = Q \cdot p_l$ $P_w = Q(p_s - p_l)$ $h = 67\%$		
Load-sensing system $P_{HG} = Q \cdot (p_s + \Delta p_{LS})$ $P_s = Q \cdot p_l$ $P_w = Q \cdot \Delta p_{LS}$ $h > 67\%$		

Table 1 – The Basic concepts of the hydraulic circuits – Noskievic, P. (1992)

The first is system characterised by constant flow. The pump is producing pressure medium characterised by constant pressure and low. The efficiency is low, because the wastes by strangling and by pressure issue of the system occurs in this circuit.

The second concept is a system characterised by constant pressure of the system. The new element in the hydraulic circuit is a sensor of the pressure. The value measured by this sensor is used for control of the flow and the result of using this sensor is decreasing of the wastes by pressure issue of the system.

The third concept is Load-Sensing system. This is the most effective method. The pressure of the system is set considering the pressure of the load. The result is reduction of the waste by strangling and by pressure issue of the system.

3 ELEKTROHYDRAULIC LOAD-SENSING SYSTEM

There exists hydraulic Load-Sensing system, which uses a pump characterised by constant angular velocity and variable volume. The main idea of a new structure - Electrohydraulic Load-Sensing system is to use a pump characterised by constant capacity and variable angular velocity, which is realised by asynchronous motor powered by frequency changer. The advantage of this concept is using the parts that are not mechanically complicated, however, there also exists a disadvantage. We have to use frequency changer.

From previous chapter we know, that this concept is producing only as much energy, as much we need and pressure of the system is little higher than pressure of the load. This means the wastes are minimal because there are minimal wastes by strangling and by pressure issue of the system.

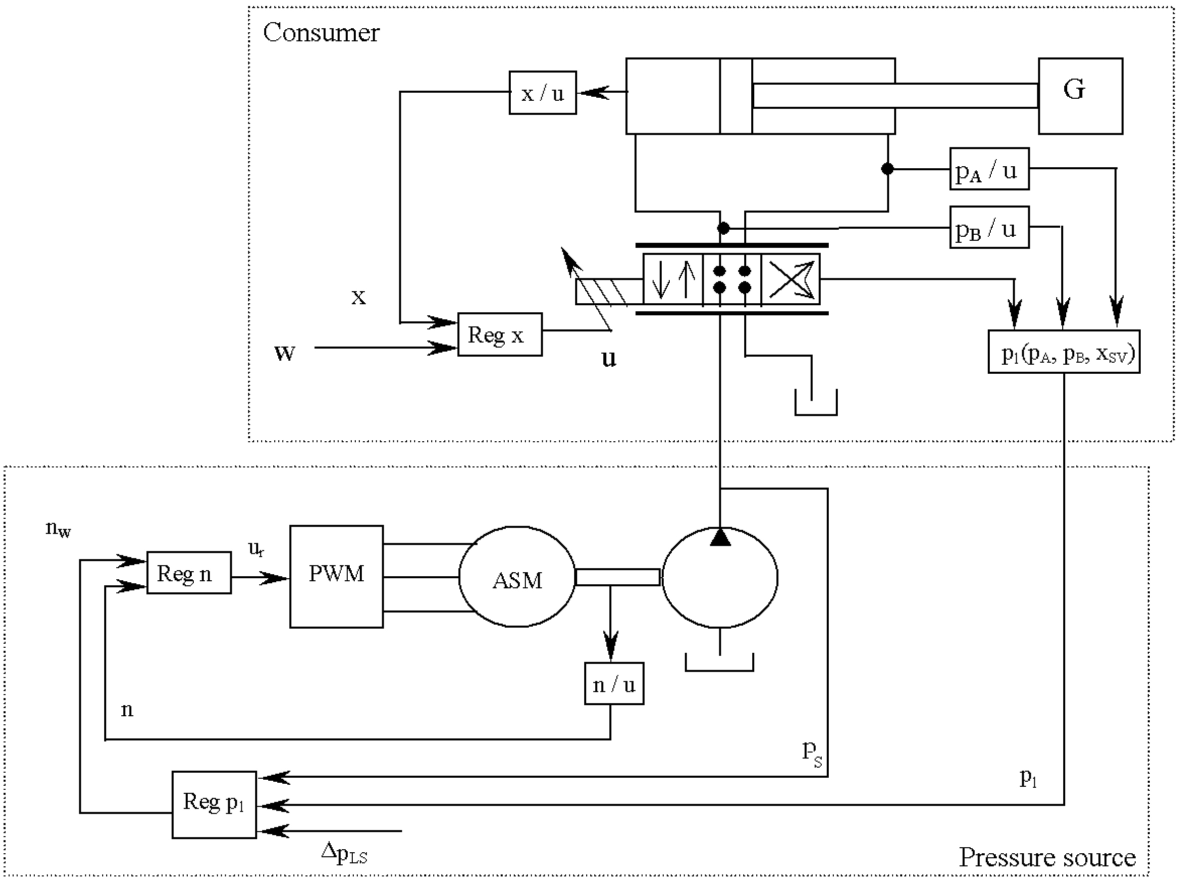


Figure 1 – Scheme of electrohydraulic Load-Sensing system

The scheme of the Load-Sensing system is presented at figure 1. As we can see, the Load-Sensing system is separable to parts, such as:

- pressure source,
- consumer,
- control loops.

4 MODEL OF ELEKTROHYDRAULIC LOAD-SENSING SYSTEM

The electrohydraulic Load-Sensing system is shown above. To make a model of this system, firstly we need to make models of subsystems.

4.1 Asynchronous motor

The asynchronous motor is changing electrical energy to torque. There are more models that can be used. I used fluxion model of asynchronous motor. The state variables of this model are magnetic fluxions. The model of Neborak, I. (1999):

$$\frac{d}{dt}\begin{bmatrix}\Psi_{SU}\\ \Psi_{SV}\\ \Psi_{RU}\\ \Psi_{RV}\end{bmatrix}=\begin{bmatrix}\frac{-R_S}{sL_S} & w_k & \frac{R_S L_h}{sL_S L_R} & 0\\ -w_k & \frac{-R_S}{sL_S} & 0 & \frac{R_S L_h}{sL_s L_R}\\ \frac{R_R L_h}{sL_S L_R} & 0 & \frac{-R_R}{sL_R} & w_k-w_m\\ 0 & \frac{R_R L_h}{sL_S L_R} & -(w_k-w) & \frac{-R_R}{sL_R}\end{bmatrix}\begin{bmatrix}\Psi_{SU}\\ \Psi_{SV}\\ \Psi_{RU}\\ \Psi_{RV}\end{bmatrix}+\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}u_{SU}\\ u_{SV}\\ u_{RU}\\ u_{RV}\end{bmatrix} \qquad (4)$$

$$M=\frac{3}{2}p_p\frac{L_h}{sL_S L_R}\left(\Psi_{SV}\Psi_{RU}-\Psi_{SU}\Psi_{RV}\right) \qquad (5)$$

$$M-M_l=I\frac{dw_m}{dt} \qquad (6)$$

4.2 The pump

The pump is source of pressure medium. There are more constructions of the pump. We can divide them into:

- tooth pump,
- plate pump,
- piston pump.

Models of all these types are same and very easy, because the flow depends on the angular velocity and the volume.

$$Q_{HG}=V_g\cdot n\cdot h_V \qquad (7)$$

$$M_{HG}=\frac{V_g}{2p\cdot h_p}\cdot p \qquad (8)$$

4.3 Pipeline

The pipeline is an area where the pump is adding pressure medium. The medium is accumulated here and the result of this is increment of the pressure – Noskievic, P. (1992).

$$\frac{dp}{dt} = \frac{k}{V_{pipeline}} \sum_i Q_i \tag{9}$$

4.4 Valve and the pressure issue of the system

The valve and the pressure issue of the system are working on the same principle - strangling. The strangling is realised by changeable hydraulic resistance – the sleeve valve.

In case of the pressure issue of the system, the pressure is on one side of the sleeve valve whereas the spring is on the opposite side. If the pressure is too high, a position of the sleeve valve overpasses a critical position and the sleeve valve starts opening itself - the hydraulic resistance decreasing. Moving of the valve is realised by electromagnetic mechanism characterised by very low time constant. We can calculate the flow in same way as for the valve and the pressure issue of the system – Noskievic, P. (1992).

$$Q = x_{relativní} B \sqrt{\Delta p} \tag{10}$$

4.5 Linear hydraulic motor

The model of linear hydraulic motor is based on moving equation of the piston rod and hydraulic capacity of the working room A and B. The Coulomb’s friction is neglected.

$$\frac{dp_A}{dt} = \frac{K}{V_A + V_{pipeline} + S_A x}\left[Q_A - S_A \frac{dx}{dt} - Q_L - Q_{LA}\right] \tag{11}$$

$$\frac{dp_B}{dt} = \frac{K}{V_B + V_{pipeline} - S_B x}\left[S_B \frac{dx}{dt} - Q_B + Q_L - Q_{LB}\right]$$

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} = S_A p_A - S_B p_B - F \tag{12}$$

4.6 Load

The main idea of the load sensing system is a system sensitive on the load. For testing the Load-Sensing system we have to design a load mechanism, which is able to change the load during one period of work. There are many ways how to do it. One of them, which I selected, is shown at the picture 2 together with the load.

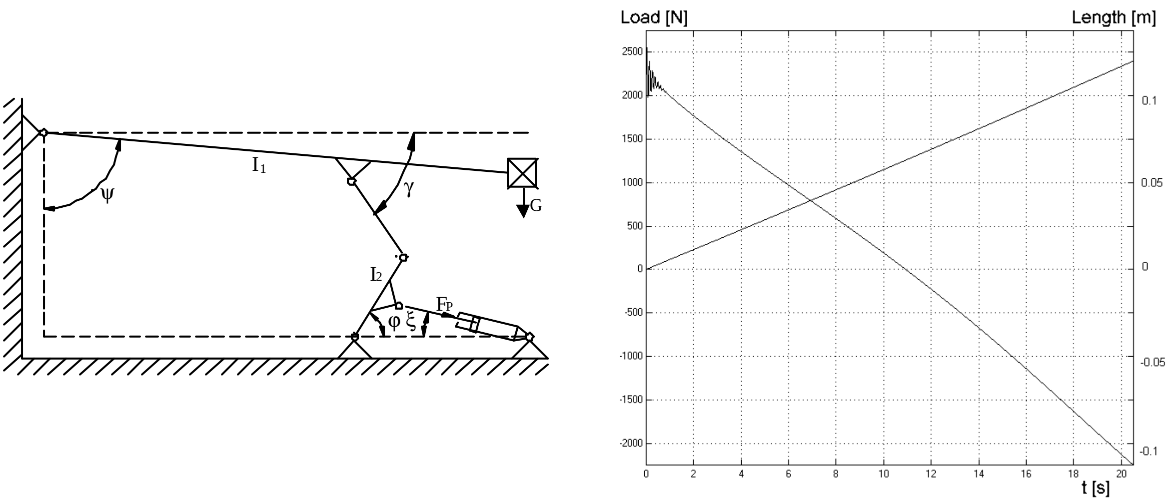


Figure 2 – The load mechanism

When I have assembled the model of load mechanism, I have considered only moving equations of the mechanism's arms I_1 and I_2. The middle arm has been ignored because its weight is minimal.

$$F_p = \frac{I_2 \cdot \ddot{\varphi} + \dfrac{I_1 \cdot \ddot{\psi} + G \cdot a \cdot \sin(\psi) + b \cdot \sin(\psi)}{b \cdot \left(\sin(\psi) \cdot \sin(\gamma) - \cos(\psi) \cdot \cos(\gamma)\right)} \cdot d \cdot \left(\cos(\gamma) \cdot \sin(\varphi) + \sin(\gamma) \cdot \cos(\varphi)\right)}{e \cdot \left(\cos(\xi) \cdot \sin(\varphi) + \sin(\xi) \cdot \cos(\varphi)\right)} \quad (13)$$

Meaning of the variables corresponds with picture above.

5 CONTROL LOOPS

At the picture 1 we can recognise control loops, which are:

- control of the consumer,
- control of the asynchronous motor,
- control of the pressure source.

Controllers and control circuits for these loops have to be designed for successful assembling of the whole Load-Sensing system's model.

6 CONTROL OF THE CONSUMER

A design of control circuit for consumer is not an easy problem, as the hydraulic motors are typically characterised by low absorption.

The hydraulic systems can be separated with reference to controlled variable as follows:

- position systems (the position is controlled),
- speed systems (the speed is controlled),
- pressure systems (the pressure is controlled).

There are many way, how to control the consumer. They are based on standard PID controllers, state controllers, fuzzy controllers etc. In my case I will use PI controller, which I modified, because the consumer consists of saturation non-linearity.

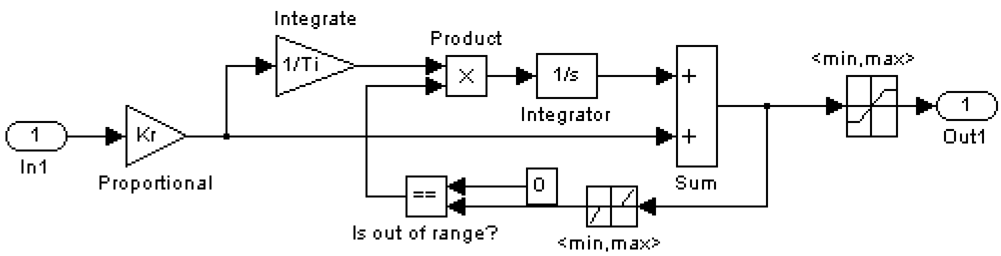


Figure 3 – Modified PI controller

The main idea of the modified PI (PID) controller is to stop integration, if the saturation limit of the input signal is reached. This is the main advantage, because if the system is returning from the saturation state, the integration part response immediately after making step over the saturation limit. However, a disadvantage exists too. Return from saturation area is made by proportional (PD) part only.

If we use a standard PI controller, the integration part does not stopped after reaching the saturation state and is still increasing itself during abidance of the system in the saturation area.

6.1 Control of the asynchronous motor

The control loop of asynchronous motor have to be solved before solving control of the pressure source, because this loop is contained inside of the pressure source.

Let us define requirements, which should be accomplished by asynchronous motor powered by frequency changer:

- time optimal response of the drive (angular speed, torque),
- non-oscillating response (angular speed, torque),
- non-sensitive controller (non sensitive to load, inertial forces),

- no permanent error.

There are two basic concepts of the frequency changers:

- current frequency changer,
- voltage frequency changer,
- voltage frequency changer with pulse width modulation (PWM).

The current frequency changer consists of current source (a rectifier, a controller of current and a choke) and current changer. The vector of current rotate with frequency f_r, vector of voltage with speed w_{su} and fluxion with speed $w_{s\Psi}$ and they are different during response. The result of this is oscillation of the torque and speed too, because the speed depends on the torque.

The voltage changer consists of AC voltage source (rectifier of voltage and capacitor) and voltage changer. The voltage is synchronised with controlling pulses. This means, that vector of the voltage rotate with angular velocity given by switching frequency. The structure has very good results in fast frequency changes, but there are problems with current picks during decreasing of frequency. The voltage frequency changers are typically used for systems with low production, like the Load-sensing systems.

The structure of the voltage frequency changer with pulse width modulation is similar to the voltage frequency changer. The difference is in switching frequency, because PWM is using frequency in kHz and the result of this is that output voltage is similar to sine wave. This structure is typically used for voltage frequency changers nowadays.

We know, that we should use PWM voltage frequency changer and now we have to select the control circuit. The offer is two basic ways:

- scalar control,
- field oriented control.

The scalar control way controls only amplitudes of the variables. The feedback signals are DC and this means uncomplicated structure. The circuit can be constructed in open or closed control loop. The advantage of this structure is price and uncomplicated structure, the disadvantage is oscillation of torque and angular velocity. This oscillation is the basic problem. In our applications of Load-sensing systems we cannot respect it, as there is danger of transferring this oscillation into the flow and the pressure.

The field oriented control way controls not only amplitudes of the variables, but also their position. This leads to more complicated structure of the circuit. The result of this is non-oscillation of the torque and the angular velocity. The disadvantage is the price.

The field oriented control can be separated into:
- indirect field oriented control,
- direct field oriented control.

This separation is based on obtaining information about the magnetic field. The indirect way uses a model and the direct way reconstructs magnetic field from measured variables.
For our application – the Load-sensing system I will use direct field oriented control and voltage frequency changer with pulse width modulation.
The mathematical model of the asynchronous motor is described by equations (14), (15) and (16) taken over Neborak, I. (1999).

$$\mathbf{u}_s = R_S \mathbf{i}_S + \frac{d?_S}{dt} + jw_X ?_S \qquad (14)$$

$$\mathbf{0} = R_R \mathbf{i}_R + \frac{d\mathbf{?}_R}{dt} + j(w_X - w)\mathbf{?}_S \qquad (15)$$

$$M = kp_P \frac{L_H}{L_R} \mathrm{Re}\{j\mathbf{?}_R \mathbf{i}_S^*\} \qquad (16)$$

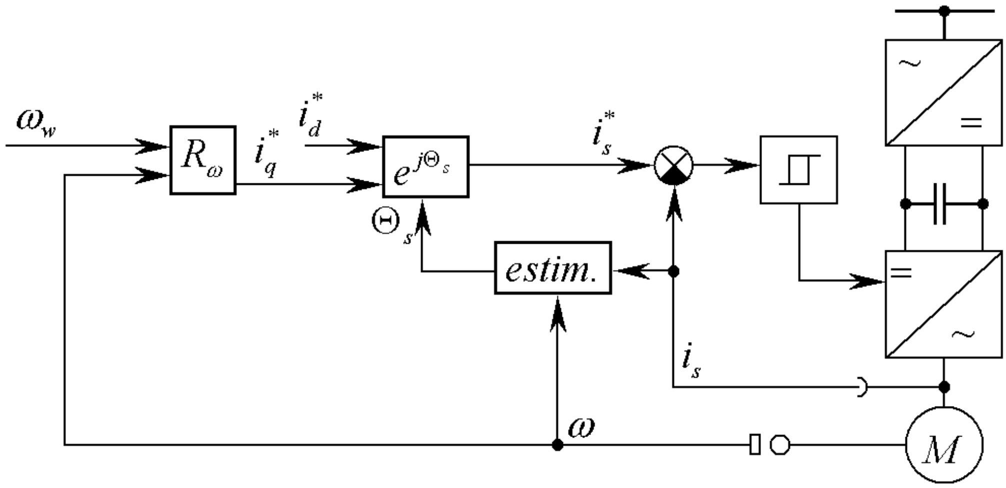


Figure 4 – Scheme of direct field oriented control

6.2 Control of the pressure source

As we can see form figure 1, the pressure source consists of an electrical drive, a pump and a pipe, which we have to involve too. The electrical drive is non-linear system consisting s of saturation non-linearity. The pipe and the pump are linear system (if we will ignore efficiency of the pump).

Let us define requirements, which should be accomplished by the pressure source:

- time optimal response of pressure
- non-oscillating response
- reduce wastes by pressure issue of the system
- reduce wastes by strangling

I have done a linearization of the system and the parameters setting of the PID controller by various methods. I made the tests by using modified PID controller (see chapter 5.1) and the best results I received by minimal regulation area method. Currently I work on a feedback state controller and the results look hopefully.

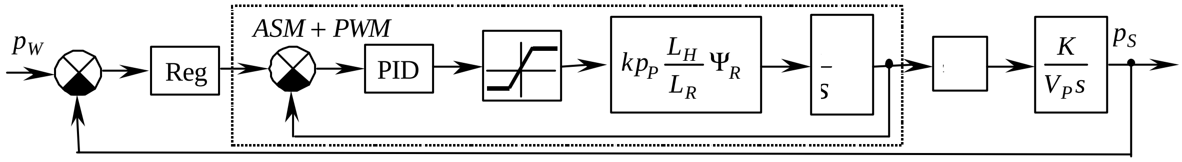


Figure 5 –Simplified model of pressure source

For solving the problem control of the pressure source, we have to remember the load. We can see at figure 2, that the load is dynamical, as we want, however, there occurs oscillation on the response which is a problem. If the load is oscillating, the given pressure of system produced by load-evaluating element will be oscillating too and this we cannot accept. We have to use a filter.

This filter should be very fast, as the system is also very fast. Therefore, we have to design low pass filter with frequency of break about 5 Hz. This is complicated problem, because the frequency of the break is very low and the filter should be very fast. I have designed such filter. It is finite impulse response filter - Kaiser 20th order.

7 SIMULATION OF THE LOAD SENSING SYSTEM

At figure 6 you can see the result of simulation of the Load-Sensing system. I have made it for the asynchronous motor MEZ 4AP112M-5, the pump Hytos MLPD/G217D, the proportional valve Bosch NG6, the linear hydraulic motor Mannesmann Rexrooth CYW 160 B 63/45-120, volume of the pipe 0.002 m^3 and the dynamical load described above.

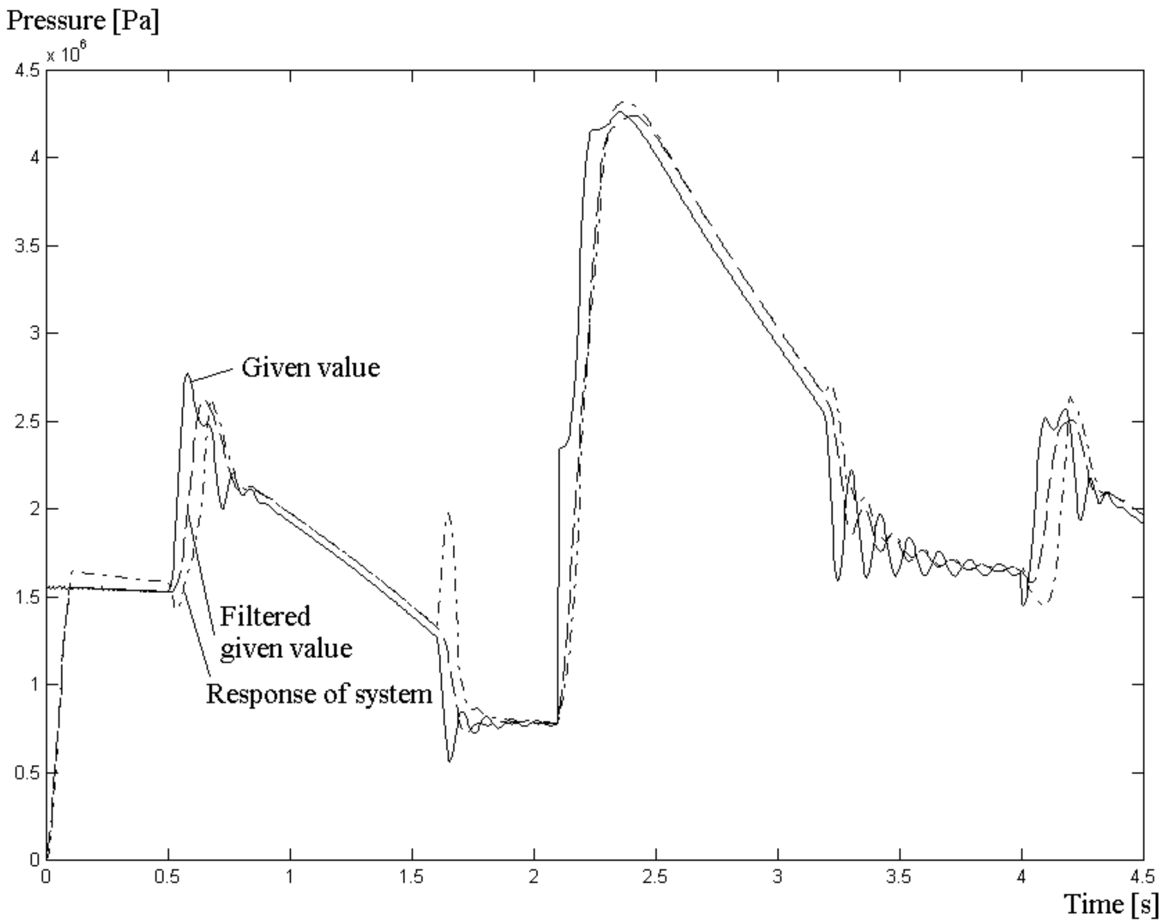


Figure 6 –The pressure responses of the system

8 CONCLUSION

The main object of my paper is the electrohydraulic Load-sensing system, it is a new concept of electrohydraulic systems and it is also the subject of my PhD study.

I present the basic concepts of the hydraulic circuits. At this part is described a system with constant flow, constant pressure and load-sensing system. I have done energetic characteristic of these hydraulic systems, as it is important for understating the main idea of the low energy cost systems. The next part consists of description of a electrohydraulic Load-sensing system. The system is itemised and models of basic elements are presented. The attention goes in control circuits consequentially. These circuits are control of the consumer, control of the asynchronous motor and control of the pressure source. The results of simulation, which I have received, are presented in the last part of the paper.

My research of the electrohydraulic Load-Sensing system continues and the next step of this research will be using a state feedback for pressure source and practical test in a laboratory.

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9 LIST OF NOTATIONS

h	Efficiency	[-]
y	Fluxion	[Wb]
s	Dissipate induction	[H]
w	Angular velocity	[rad/s]
B	Coefficient of strangling	$[m^3Pa^{1/2}s^{-1}]$
F	Force	[N]
I	Torque of inertia	[kg·m]
k	Gain	[-]
L	Inductivity	[H]
M	Torque	[Nm]
n	Speed	[1/s]
P	Production	[W]
p	Pressure	[Pa]
p_p	Number of pole-pairs	[-]
Q	Flow	$[m^3/s]$
R	Resistance	[Ω]
u	Voltage	[V]
V	Volume	$[m^3]$
x	Position	[Nm]

Indexes

A	Working room A
B	Working room B
HG	Relation with pump
l	Relation with load
L	Leakage
p	Relation with pressure
Q	Relation with flow
R	Relation with rotor
s	Relation with system
S	Relation with stator
U	Reference to co-ordinate U
V	Reference to co-ordinate V

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