Design of Controllers With Fixed Order for Hydraulic Control System With a Long Transmission Line

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This paper presents the problem of describing the system, a pump-controlled motor with a long transmission line, by means of a mathematical model with lumped parameters, where the long transmission line is divided into n equal "Π" segments. The obtained mathematical model is of high order but by applying the corresponding methodology in this paper, its order will be reduced, which considerably increases its use value. From the aspect of control, here it is important how to solve the problem of control of high order facilities because controllers with fixed order are present in industrial practice (P, PI, PID), and the high order facility should be controlled. This paper represents the beginning of research in defining the methodologies of synthesis of controllers with fixed order for the systems with long transmission lines.

Keywords: *control system, modelling, transmission line, controllers, distributed parameters, lumped parameters.*

1. INTRODUCTION

Increasingly strict and wide requirements regarding displacement hydrostatic power transmitters have recently appeared in the sense of simultaneous accomplishment of high power exploitation degrees, high speed of response with the reduction of price [1-3]. This particularly refers to high power systems and systems of variable load (building and mining machines, agricultural machines, transportation machines, machine tools, etc). It is obvious that these requirements result in the need for more intense development of systems with displacement control in relation to the systems with damping control. One of the main preconditions for quality and reliable operation of high power systems is stable and quality operation of the system for automatic regulation of hydrostatic power transmitter, the pump controlled motor with long hydraulic lines (Fig. 1). The authors of this paper have considered the problem of dynamic behaviour of such systems in a very systematic way, and the results are presented in paper [4-5]. The existence of a long transmission line in this system makes its dynamics more complex to a considerable extent, because the physical values, pressure and flow, which characterize the transfer of energy along the long transmission line depend both on the time coordinate and the space coordinate. Dependence of these physical values on the space coordinate, too, conditions that during mathematical description of the long transmission line the space distribution cannot be neglected, so that it is described by a model with distributed parameters. Models with distributed parameters are described by differential equations and the model thus obtained is of infinitesimally high order [6-10]. In addition to mathematical modelling of the long transmission line by means of a model with distributed parameters, it is possible to describe the long transmission line by common differential equations, i.e. a model with lumped parameters [1-5] because solving common differential equations makes considerably fewer difficulties in comparison with solving partial differential equations.

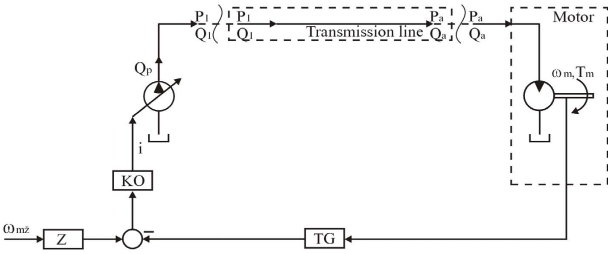

Figure 1. Symbolic diagram of a closed system of automatic control of a pump-controlled motor with a long transmission line

This paper presents the problem of describing the system, a pump-controlled motor with a long transmission line, by means of a mathematical model with lumped parameters, where the long transmission line is divided into n equal "Π" segments. The obtained mathematical model is of high order but by applying the corresponding methodology in this paper, its order will be reduced, which considerably increases its use value. From the aspect of control, here it is important how to solve the problem of control of high order facilities because controllers with fixed order are present in industrial practice (P, PI, PID), and the high order facility should be controlled [10-14]. This paper represents the beginning of research in defining methodologies of synthesis of controllers with fixed order for the systems with long transmission lines described by means of mathematical models of high order, and it treats the methodology of designing P regulators, whose introduction can significantly

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influence the improvement of quality of dynamic behaviour of these systems.

2. DYNAMIC MATHEMATICAL MODEL OF THE SYSTEM OF A PUMP-CONTROLLED MOTOR WITH A LONG TRNASMISSION LINE

The mathematical model of the system is determined by describing every element of SAR by fundamental equations, with the corresponding assumptions. The structure of a part of the system, on the basis of which modelling is performed, is presented in Figure 2.

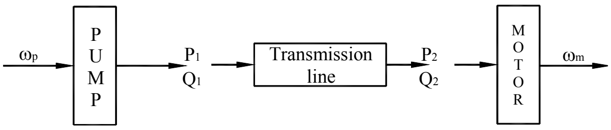

Figure 2. Structural diagrams of the subsystem [1]

2.1 Pump

The pump is of variable working volume with the constant number of revolutions. Leakage and compressibility of oil in the pump are taken into consideration through the coefficient of leakage resistance R_p and the module of compressibility B. The flow at the exit of the pump, $Q_p = Q_1$, is equal to the flow at the beginning of the long transmission line and is described by the equation:

$$Q_1(t) = D_p(t)\omega_p - \frac{1}{R_p} p_1(t) - C_p \frac{\mathrm{d}p_1(t)}{\mathrm{d}t} . \qquad (1)$$

By applying the Laplace Transform, Equation (1) at all initial conditions equal to zero obtains the following form:

$$Q_1(s) = D_p(s)\omega_p - \frac{1}{R_p} p_1(s) - C_p s p_1(s) \qquad (2)$$

$$Q_1(s) = D_p(s)\omega_p - Z_p p_1(s) \qquad (3)$$

where: $Z_p(s) = C_p s + \frac{1}{R_p}$; $C_p = \frac{V_p}{B}$.

2.2 Hydro-motor

The hydromotor is of constant working volume with a variable number of revolutions. Leakage and compressibility of oil in the motor are covered through the characteristic coefficients R_m and C_m, respectively. The flow at the exit of the long transmission line is equal to the flow at the hydromotor $Q_2 = Q_m$ and is described by the equation:

$$Q_2(t) = D_m\omega_m(t) + \frac{1}{R_m} p_2(t) + C_m \frac{\mathrm{d}p_2(t)}{\mathrm{d}t} . \qquad (4)$$

By applying the Laplace Transform, Equation (4) at all initial conditions equal to zero obtains the following form:

$$Q_2(s) = D_m\omega_m(s) + \frac{1}{R_m} p_2(s) + C_m s p_2(s) \qquad (5)$$

$$Q_2(s) = D_m\omega_m(s) + Z_m p_2(s) \qquad (6)$$

where: $Z_m(s) = C_m s + \frac{1}{R_m}$; $C_m = \frac{V_m}{B}$.

The loads which should be overcome by the hydromotor are: inertial, viscous, and external. The moment equation of hydromotor load is given in the following form:

$$D_m p_2(t) = J_m \frac{\mathrm{d}\omega_m(t)}{\mathrm{d}t} + B_v\omega_m(t) + T_L(t) . \qquad (7)$$

By applying the Laplace Transform, Equation (7) at all initial conditions equal to zero obtains the following form:

$$D_m p_2(s) = J_m s\omega_m(s) + B_v\omega_m(s) + T_L(s) . \qquad (8)$$

By transforming (8), the following expression for pressure at the end of the long transmission line is obtained:

$$p_2(s) = Z_T D_m\omega_m(s) + \frac{T_L(s)}{D_m} \qquad (9)$$

where: $Z_T = \frac{J_m}{D_m^2} s + \frac{B_v}{D_m^2}$ – the characteristic impedance of internal load at the hydromotor.

2.3 Long transmission line

The long transmission line represents the connection between the pump and the hydromotor. As the length of transmission lines ranges between several meters and several dozen meters, it is clear that pressures and flows at the beginning and at the end of the line are not equal, so that its influence in such systems cannot be neglected.

Figure 3 presents the symbolic scheme of a transmission line modelled through a "Π" approximate model with lumped parameters. In this model, the initial assumption is that the overall volume of the transmission line $V = A \cdot l$, is divided into two parts and concentrated at its ends with the equivalent module of compressibility E and the flow in the middle of the transmission line Q_e, so that this model is called "the model of medium flow" in literature [1]. In other parts of the long transmission line, the working fluid is considered incompressible, and the line itself is considered non-elastic.

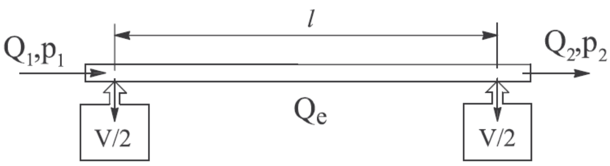

Figure 3. Symbolic scheme of the transmission line modelled by a "Π" approximate model with lumped parameters

This model can also be presented through its equivalent electrical analogy in the form of a simple electric circuit shown in Figure 4.

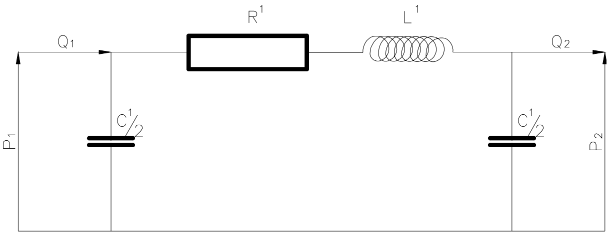

Figure 4. Equivalent electrical analogy of the "Π" scheme of a transmission line with lumped parameters

By solving this electric circuit, the equations connecting the pressures and flows at the beginning and at the end of the long transmission line are obtained:

$$p_1(s) = (1 + \frac{Z^1 Y^1}{2}) p_2(s) + Z^1 Q_2(s) \tag{10}$$

$$Q_1(s) = Y^1 (1 + \frac{Z^1 Y^1}{4}) p_2(s) + (1 + \frac{Z^1 Y^1}{2}) Q_2(s) \tag{11}$$

where: Z^1 – the equivalent impedance of the described hydraulic circuit; Y^1 – the equivalent admittance of the described hydraulic circuit

$$Z^1 = R^1 + L^1 s \; ; \; Y^1 = C^1 s \; ;$$
$$R = R \cdot l \; ; \; L = L \cdot l \; ; \; C = C \cdot l \tag{12}$$

$$R = \frac{128\mu}{\pi d^4} \; ; \; L = \frac{\rho}{A} \; ; \; C = \frac{A}{\rho c^2} = \frac{A}{E} \tag{13}$$

and represent the resistance, inductivity and capacity of the transmission line, respectively (μ – the coefficient of dynamic viscosity of the working fluid; d – the diameter of the transmission line; ρ – the density of the working fluid in the transmission line; A – the area of the cross-section of the transmission line; E – the equivalent modulus of elasticity; c – the velocity of sound in the fluid).

The transmission matrix for the "Π" model with lumped parameters is given by the equation:

$$\begin{bmatrix} p_1 \\ Q_1 \end{bmatrix} = \begin{bmatrix} (1 + \frac{Z^1 Y^1}{2}) & Z^1 \\ Y^1 (1 + \frac{Z^1 Y^1}{4}) & (1 + \frac{Z^1 Y^1}{2}) \end{bmatrix} \cdot \begin{bmatrix} p_2 \\ Q_2 \end{bmatrix} . \tag{14}$$

The equation describing the connections between the flow and the pressure at the end and at the beginning of the transmission line is given in the form of a transmission matrix [15].

$$\begin{bmatrix} p_1(s) \\ Q_1(s) \end{bmatrix} = \begin{bmatrix} A_L & B_L \\ C_L & D_L \end{bmatrix} \cdot \begin{bmatrix} p_2(s) \\ Q_2(s) \end{bmatrix} . \tag{15}$$

Equation (15) represents the general form of the transmission matrix of the long transmission line with lumped parameters. The values of parameters A_L, B_L, C_L and D_L in (15) correspond to the values from (14).

By linking (15) with (3), (6) and (9) and on the basis of the characteristics of the coefficients of the long transmission line: $A_L = D_L$ and $A_L D_L - B_L C_L = 1$, the transmission function of a part of the system of automatic regulation is obtained in the following form:

$$D_m \omega_m(s) = \frac{D_p(s)\omega_p - \left[\left(Z_m + Z_p \right) A_L + Z_m Z_p B_L + C_L \right] \frac{1}{D_m} T_L(s)}{\left(1 + Z_m Z_T + Z_p Z_T \right) A_L + \left(Z_p + Z_p Z_m Z_T \right) B_L + Z_T C_L} . \tag{16}$$

Equation (16) represents a mathematical model of a part of the automatic control system, when the long transmission line is modelled as a "Π" segment with the length l. However, since transmission lines can be several dozen meters long, then observation of the long transmission line as a "Π" segment with the length l would not cover the complete dynamics of the very physical process taking place along the transmission line. Therefore, the transmission line is divided into n equal "Π" segments with the length l/n for the purpose of obtaining an adequate mathematical model of a long transmission line and hence of a described system of automatic regulation.

Figure 5. The transmission line divided into n segments of equal length *l*/n

As:

$$\begin{bmatrix} p_1(s) \\ Q_1(s) \end{bmatrix} = \begin{bmatrix} A_L & B_L \\ C_L & D_L \end{bmatrix} \cdot \begin{bmatrix} p_2(s) \\ Q_2(s) \end{bmatrix} ;$$
$$\begin{bmatrix} p_2(s) \\ Q_2(s) \end{bmatrix} = \begin{bmatrix} A_L & B_L \\ C_L & D_L \end{bmatrix} \cdot \begin{bmatrix} p_3(s) \\ Q_3(s) \end{bmatrix} ;$$
$$\begin{bmatrix} p_{n-1}(s) \\ Q_{n-1}(s) \end{bmatrix} = \begin{bmatrix} A_L & B_L \\ C_L & D_L \end{bmatrix} \cdot \begin{bmatrix} p_n(s) \\ Q_n(s) \end{bmatrix} . \tag{17}$$

Linking of these equations results in:

$$\begin{bmatrix} p_1(s) \\ Q_1(s) \end{bmatrix} = \begin{bmatrix} A_L & B_L \\ C_L & D_L \end{bmatrix}^n \cdot \begin{bmatrix} p_n(s) \\ Q_n(s) \end{bmatrix} . \tag{18}$$

Now, the basic elements of the long transmission line figuring in the polynomials A_L, B_L, C_L and D_L have the values:

$$R^1 = R \cdot \frac{l}{\text{n}} \; ; \; L^1 = L \cdot \frac{l}{\text{n}} \; ; \; C^1 = C \cdot \frac{l}{\text{n}} . \tag{19}$$

By using the program package Matlab, a program linking (18) with (3), (6) and (9) is written, so that a mathematical model of the described system is obtained in the form of the transmission function $W_1(s)$ of a part of the automatic control system for the finite number n of equal "Π" segments with the length l/n.

3. DYNAMIC BEHAVIOUR OF THE SYSTEM CONTROLLED BY A "P" REGULATOR

The simulation of dynamic behaviour was performed in the program package Matlab on the basis of the block diagram of the described system presented in Figure 6.

The transmission function of the open circuit on the block diagram has the following form:

$$W_{ok} = K_a K_{TG} \frac{\omega_p}{D_m} W_1(s) = K_{ok} W_1(s) \tag{20}$$

where:

$$K_{ok}=K_a K_{TG}\frac{\omega_p}{D_m}$$

$$W_1(s)=\frac{1}{\left(1+Z_m Z_T+Z_p Z_T\right)A_L+\left(Z_p+Z_p Z_m Z_T\right)B_L+Z_T C_L}. \quad (21)$$

The parameters at which the simulation was performed: E = 1.44 · 10^9 N/m^2; ρ = 860 kg/m^3; μ = 0.033 Ns/m^2; R_p = R_m = 1 · 10^{10} Nm^{-2}/m^{3}s^{-1}; Q_{ref} = 2.5 · 10^{-4} m^3/s; d = 10 · 10^{-3} m; l = 16 m; c = 1290 m/s; D_m = 2.61 · 10^{-6} m^3/rad; B_v = 1 · 10^{-3} Nms; I_m = 6.9 · 10^{-3} kgm^2; B = B_p = B_m = 1.2 · 10^9 N/m^2; K_{TG} = 1 · 10^{-2} V/rad/s.

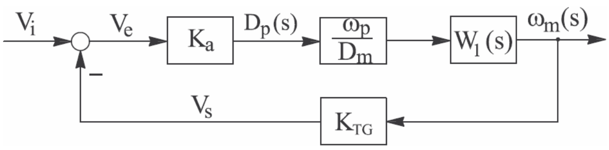

Figure 6. Block diagram of the system

Figure 7 presents the hodograph of the frequent characteristic of the open circuit in the 16-meter transmission line divided into 16 equal segments! To determine the stability limit, the Nyquist and Bode criterion was used (Fig. 8) on the basis of which the value K_{ok}, for which the system is marginally stable, was determined. Figure 8 also presents the Bode diagrams when the line is divided into 4 equal segments, on the basis of which it can be seen that up to certain frequencies there are no significant deviations between the models of the line divided into 16 and 4 equal segments. The gain limit *OK* remains the same even when the dynamics of the long transmission line is covered by its division into 4 equal segments.

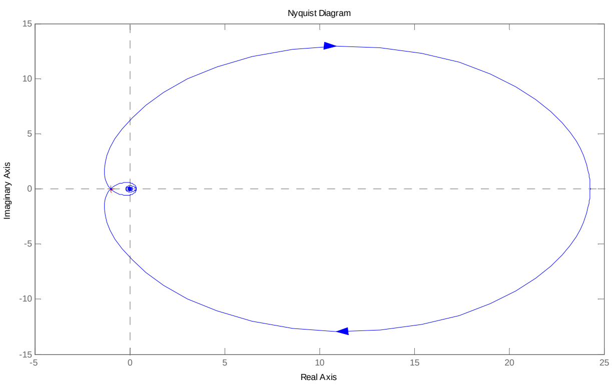

Figure 7. Phase-frequent characteristic *OK* at n = 16, *l* = 16 m, K_{ok} = 30.3

Figure 9 presents the system response to the unit step change of input. The comparative presentation of the system responses for different divisions of the long transmission line with the length l = 16 m into equal segments is shown. If n = 0, then the dynamics of the line, although the line physically exists, is not covered by the mathematical model. At n = 1, the transmission line with the length of 16 m is observed as a "Π" segment, and its dynamics is now covered by the mathematical model of the system. Figure 9 also presents the system responses at n = 4 and n = 16 segments. As with the frequency criterion, in the time domain it was shown that deviations in the response in the division of the transmission line into 16 and 4 equal segments is small and can be neglected. Every division of the transmission line into more than 4 segments gives slightly better results from the aspect of the system response. Divisions of the transmission line into up to 3 segments allow considerable deviations in the response and must not be neglected, before all, from the aspect of system stability.

This imposes the conclusion that the dynamics of the transmission line in the mathematical model of the described system is best presented by the division of the transmission line into 4 segments of the same length. Division into 4 segments does not disturb the stability limit, deviations in the response are small, and the order of the described system is considerably reduced. For the line division into 16 segments, the system is of the 34th order, while for the one with 4 segments, it is of the 10th order.

Figure 10 presents the system response in the division of the line into 16 equal segments with different lengths of l = 0, 4, 8 and 16 for the boundary gain value of the open circuit K_{ok} = 30.3. On the basis of the results of simulation shown in Figure 10, it is seen that at smaller lengths of the transmission line, its dynamics has a considerably smaller influence on the behaviour of the whole automatic control system.

On the basis of the results of simulation in the frequency and time domains of the described automatic control system controlled by a P regulator, the optimum number of segments in which the transmission line is l = 16 m long should be divided is determined, and its dynamics in the overall mathematical model of the system could thus be adequately covered. It was established that in the division of the transmission line of this length, its division into 4 equal segments gives satisfactory results from the aspect of stability and response of the described system, and the order of the system is considerably reduced. Figure 11 presents the system response in the division of the transmission line with the length of 16 m into 4 equal segments for three values of the gain factor of the open circuit K_{ok} = 30.3 when the system is marginally stable, K_{ok} = 20.3 and K_{ok} = 15 from the range of stable operation of the system. From these diagrams, it is clearly seen that the reduction of gain of the P regulator influences the reduction of step from 111 to 29.9 %. Further reduction of gain would considerably contribute to the reduction of step, but it would have negative influence on the error and the speed of response of the described system.

4. APPLICATION OF CONTROLLERS WITH TWO DEGREES OF FREEDOM

As the problem of step occurring in these systems cannot be efficiently solved by a classical P regulator without disturbing the speed of response and the static error of the regulated value, a regulator proposed by Horowitz [12], which enables the correct following of the given desired reference, is introduced. By introducing the additional regulator whose transmission function is $W_R(s)$, the described system is controlled by a regulator with two degrees of freedom because it has, in addition

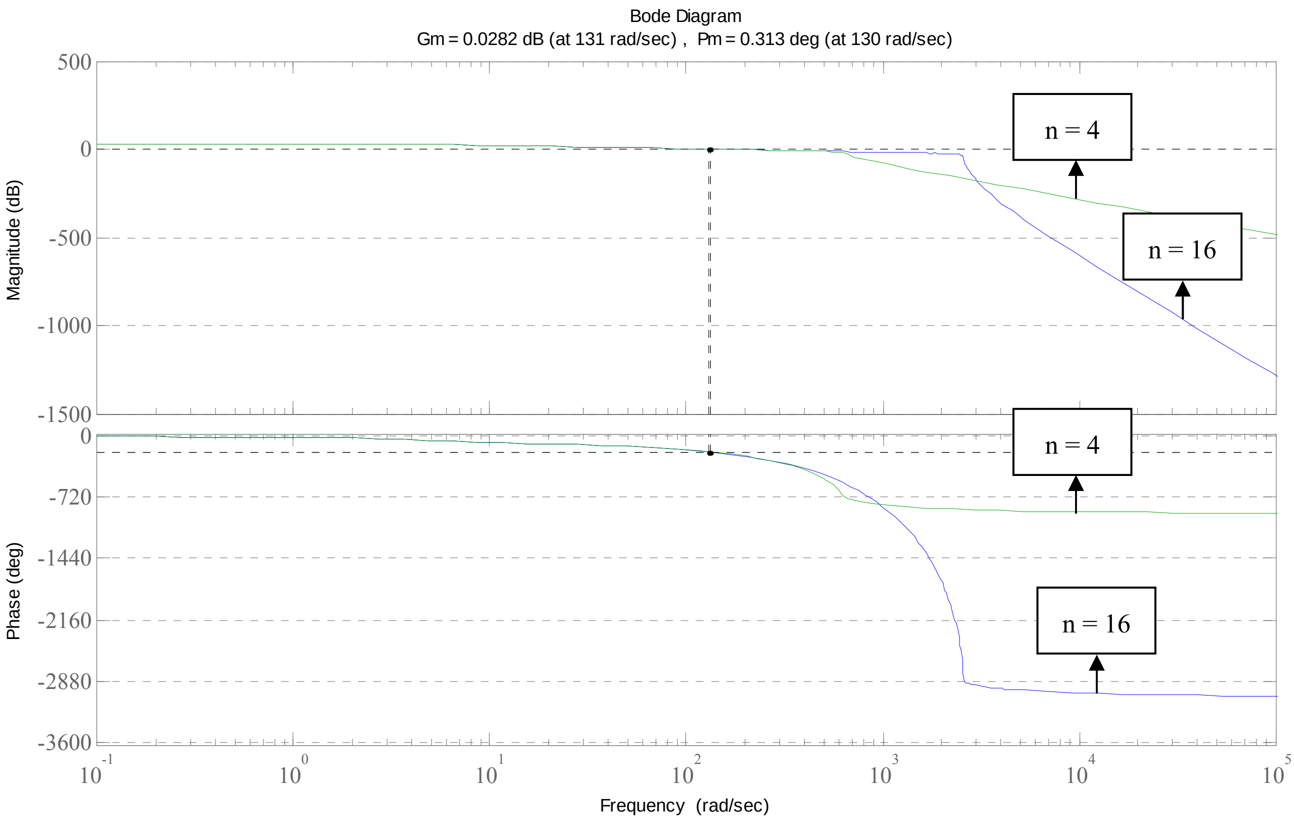

Figure 8. Logarithm frequency characteristic *OK* at n = 16, n = 4 and l = 16 m K_{ok} = 30.3

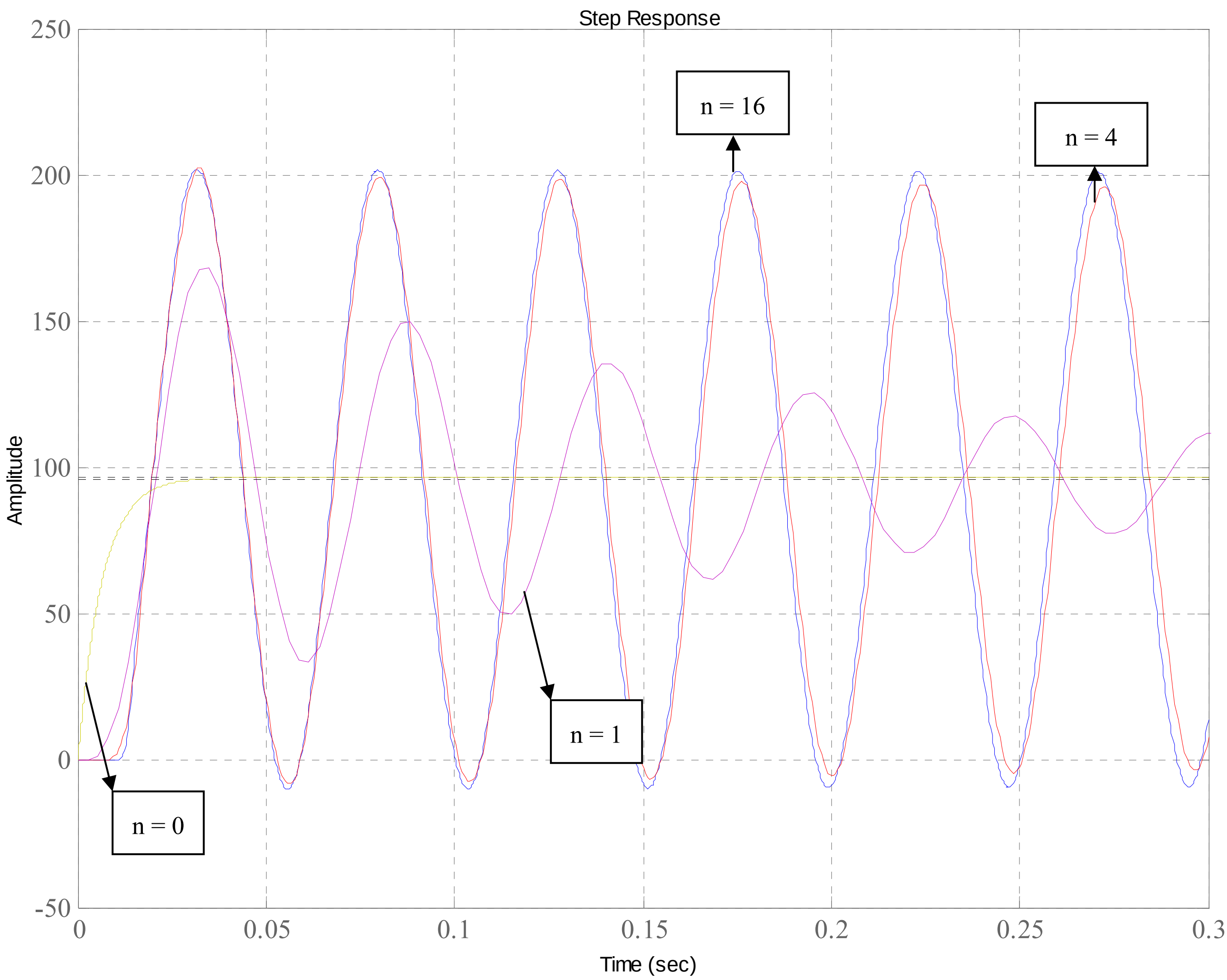

Figure 9. The system response in the line division into n = 0, 1, 4 and 16 segments at the transmission line length *l* = 16 m

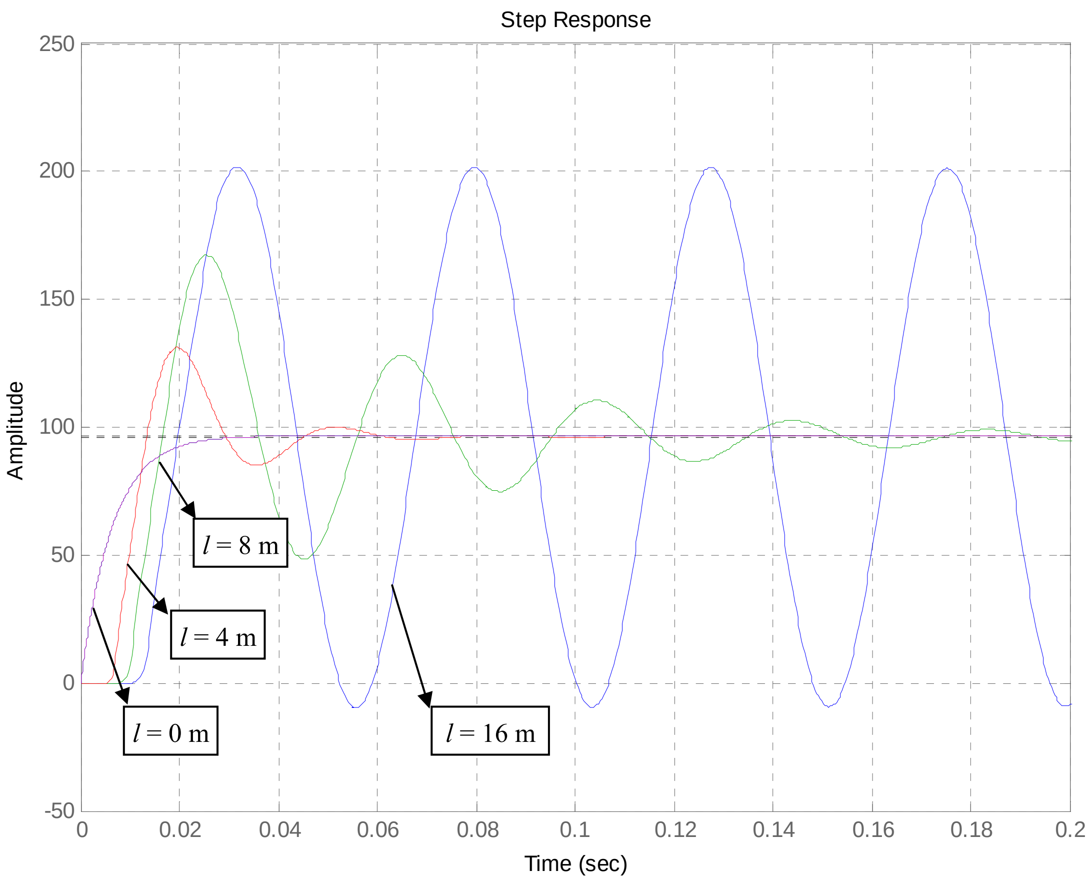

Figure 10. The system response in the line division into n = 16 segments at the transmission line length l = 0, 4, 8 and 16 m and the gain value K_{ok} = 30.3

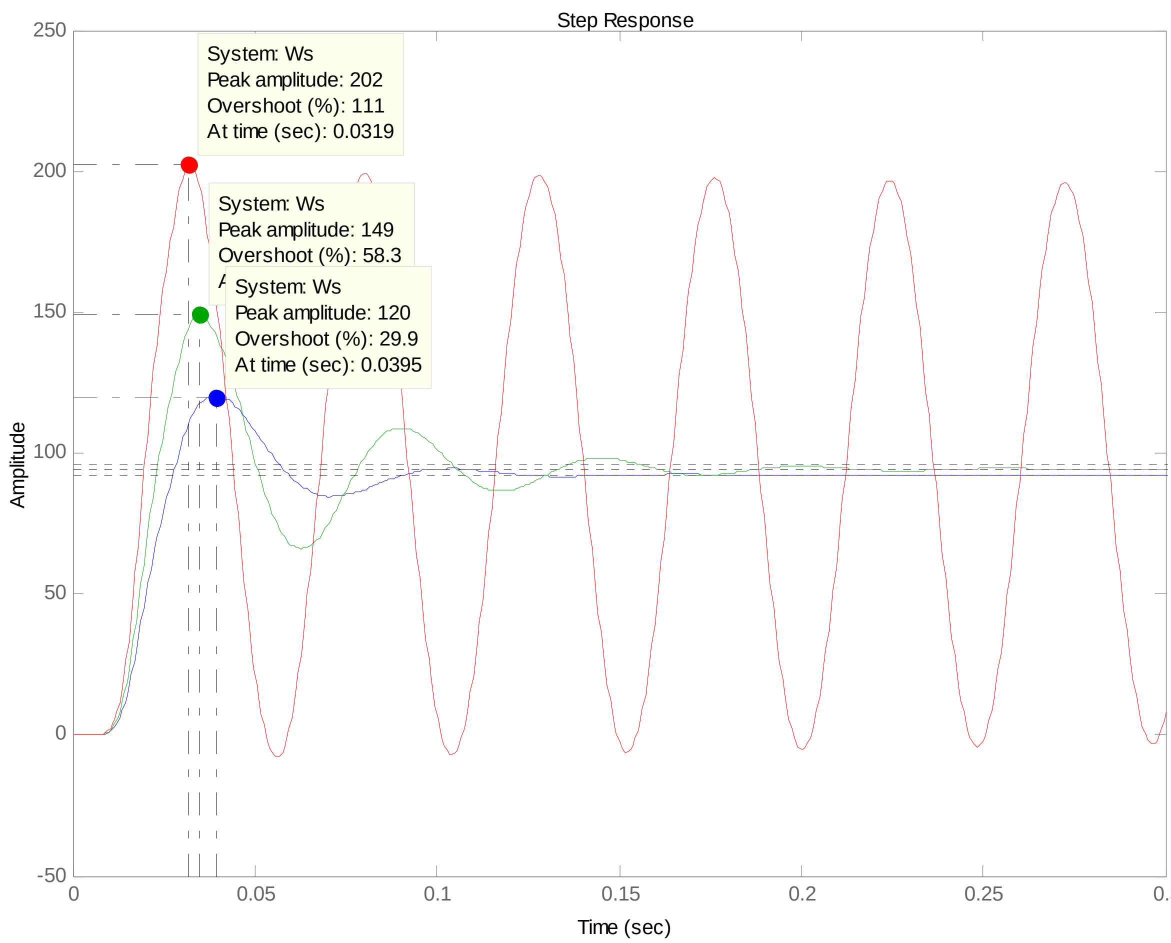

Figure 11. The system response in the line division into n = 4 segments at the transmission line length l = 16 m, for the gain value K_{ok} = 30.3, 20.3 and 15

to the classical P regulator, another regulator according to the given desired reference (Fig. 12). The transmission function of the regulator according to the reference $V_d(s)$ has the form $W_R(s) = (\tau_1 s + 1)/(\tau_2 s + 1)$. By selecting the time constants $\tau_1 = 0.03$ s and $\tau_2 = 0.05$ s, where it is obvious that $\tau_2 > \tau_1$, which would reduce the speed of response of the system. Simulation in the program package Matlab in Figure 13 presents a comparative diagram of the system responses when it is controlled by the classical P regulator and the regulator with two degrees of freedom. From Figure 13 it can be seen that we succeeded in reducing the step from 58.3 to 10.3 % with a slight reduction of speed of response by about 2 ms, by using the regulator with two degrees of freedom for control of the system described in Figure 12.

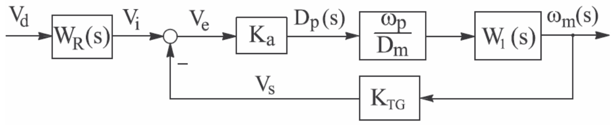

Figure 12. Block diagram of the system controlled by the regulator with two degrees of freedom

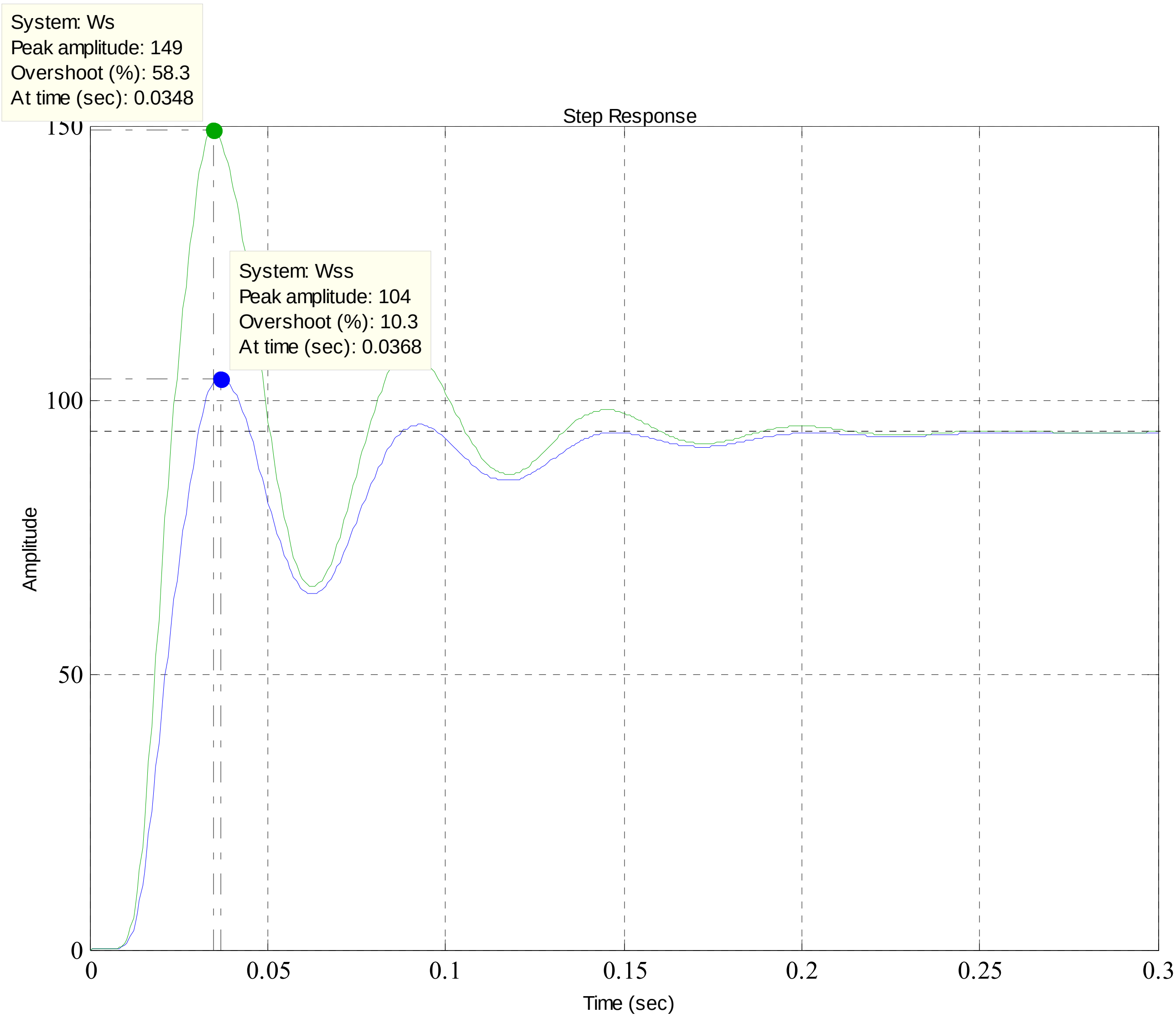

Figure 13. Comparative response of the system in the division of the line into n = 4 segments at the length of the transmission line of *l* = 16m, controlled by a P regulator and the regulator with two degrees of freedom

5. CONCLUSION

On the basis of the analysis in the frequency and time domains of a transmission system with a long transmission line, it can be concluded as follows:

- That it is possible to reduce the high order of the described system several times by adequate selection of division of the long transmission line into the optimum number of segments;
- That the reduction of the length of the transmission line, when possible, can reduce the influence of dynamics of the transmission line on the dynamics of the whole system. The influence of dynamics of the transmission line on the behaviour of the whole system increases with the increase of its length;
- That selection of the corresponding gain of the P regulator can considerably influence the reduction of step, and hence the increase of error and reduction of speed of the system response;
- That control of the described system by means of a regulator with two degrees of freedom can solve the problem of step, with a slight reduction of the speed of response;

- That design of appropriate controllers with fixed order can considerably influence the quality of dynamic behaviour of these systems and improvement of their performance.

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ПРОЈЕКТОВАЊЕ РЕГУЛАТОРА ФИКСНЕ СТРУКТУРЕ ЗА ХИДРАУЛИЧНЕ СИСТЕМЕ УПРАВЉАЊА СА ДУГАЧКИМ ВОДОВИМА

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У овом раду је изложена проблематика система пумпно управљаног мотора са дугачким хидрауличним водовима, математичким моделом са концентрисаним параметрима где је дугачки хидраулични вод подељен на n једнаких „П“ сегмената. Тако добијен математички модел је вишег реда, али применом одговарајуће методологије, његов ред ће бити редукован и тиме знатно повећана његова употребна вредност. Са аспекта управљања, овде се појављује проблем, како решити проблем управљања објекта вишег реда, јер су у индустријској пракси присутни само регулатори фиксне структуре (П, ПИ, ПИД) а треба управљати објектом вишег реда. Овај рад представља почетак истраживања у циљу дефинисања методологије синтезе регулатора фиксне структуре за хидрауличне системе са дугачким водовима који су описни математичким моделима вишег реда, такође, у њему је обрађена и методологија пројектовања П регулатора чијим се увођењем у знатној мери може утицати на побољшање квалитета динамичког понашања ових система.