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Optimization of the control loops of the variable frequency induction motor drive of the flame reactor feed screw

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Abstract

In the paper the optimization of the control loops of the variable frequency induction motor drive for the feed screw of a flame reactor has been carried out to obtain required dynamic characteristics of the electric drive for known parameters of the plant. Simulation studies of basic control loops (current, flux-linkage and speed) are performed and dynamic parameters of control quality are presented. Results of the studies show that the obtained parameters meet requirements of the workflow and the modern variable-frequency drive based on induction motor can be implemented for actuating the feed screw of flame reactor. It should also be mentioned that transients quality factors in speed loop with input filter are better than without it.

Keywords: variable frequency induction motor, electric drive, optimization, control loop.

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1. Introduction

The workflow of uranium fluorination requires precise dosing of uranium oxide, reliability and safety of the electric drive of feed screw. The technological process need to be controlled in real time mode, since the accurate proportion of the dosed solid powder of uranium oxide and the gaseous fluorine is needed to maximum degree of uranium extraction into UF6 while minimum consumption of fluorine. If the techno-logical parameters of uranium oxides fluorination are not close to the normal values, the dynamics of the burning process is altered, and the corrosion rate for construction materials of the flame reactor is in-creased, which causes shortening of its life. The dosing process of radioactive uranium oxides into a covered by a protection coating apparatus (flame reactor) is carried out by indirect volumetric method by controlling the speed of feeding screw. That is why we need to control both its speed and mechanical torque on its shaft.

Currently, a DC motor is used as the electric drive of the screw, which serves to feed the flame reactor with uranium oxide in the form of fine-grained material. The feeder is weigh and single-component batcher according to classification in [1], i.e. it measures the weight of the single bulked material. Another feature of the driven mechanism is its big value of distributed moment of inertia, as a feature of all “barrel” reactor feeders [2].

Disadvantages of the DC motor drive are the low reliability of the DC drive because of the brush-collector junction, maintenance complexity, high operating costs, large dimensions and weight. Using electric drive based on the induction motor with squirrel-cage rotor and the implementation of modern control methods provides high efficiency and performance of these drives. Extensive use of induction motor with squirrel-cage rotor in a general-purpose and specialized electric drives is caused by it’s high reliability due to the absence of brush-collector junction and permanent magnets, simple construction, small size and moment of inertia and no restrictions on switching from speed and current, etc. [3, 7-9].

Therefore, the development, research and implementation of modern variable-frequency drive based on induction motor for the flame reactor feed screw is relevant and meets the modern requirements [4, 10-12].

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2. Optimization of control loops of frequency-variable induction motor drive system

Unique feature of variable frequency electric drives is relatively big lag in feedback of current, flux and speed loops [5, 13]. Therefore, classic optimization theory of subordinate regulation systems with non-inertia feedback can't be applied for their optimization. For optimization of the control loops with inertial feedback the methods stated in [6, 14] can be used. Simplified structure diagram of variable frequency electric drive is shown in fig. 1.

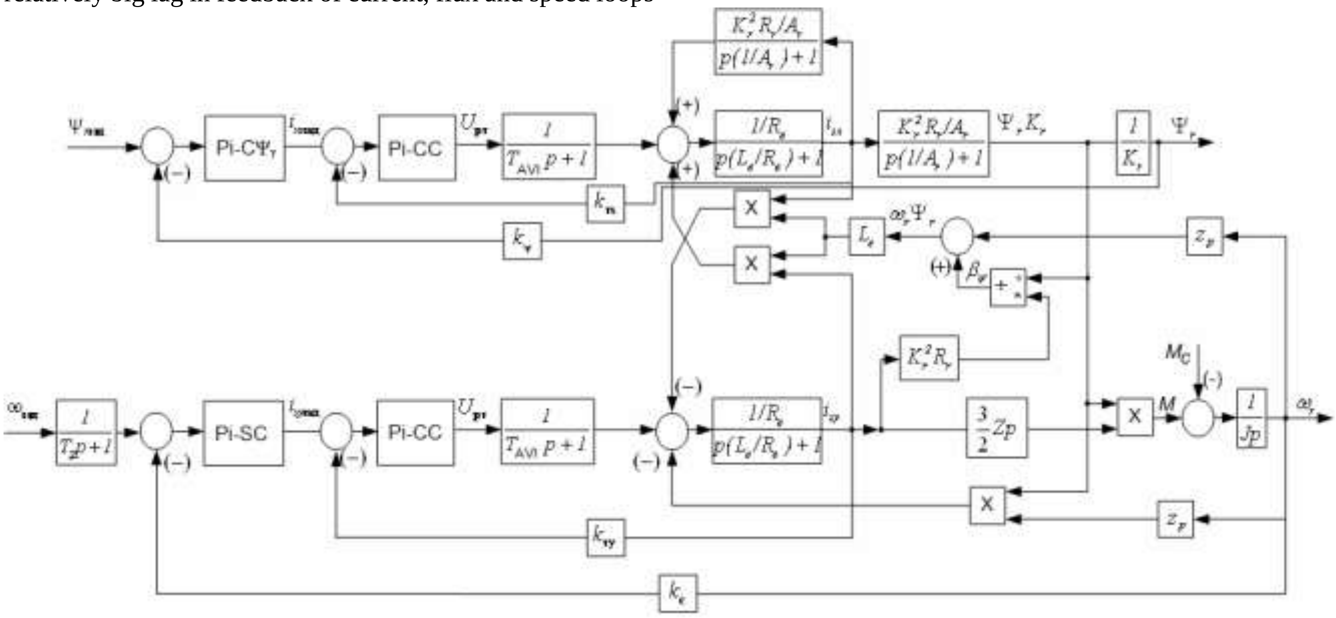

Figure 1. Simplified structure diagram of variable frequency vector control of the induction motor drive

From this diagram we can see that the system has control loops of the stator current X and Y components (with current controllers for each axis CCx and CCy), speed (with speed controller SC) and regulation loop, that determines the rotor winding flux (with flux controller FC.

3. Current loop optimization

Current loop optimization is performed without considering motor cross-couplings and with zero references for speed and flux. Loop structure diagram is shown in fig. 2.

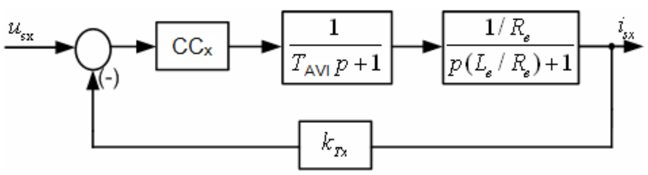

Figure 2. Structure diagram of the loop for stator current component control

Considering the loop parameters a proportional-integral (PI) controller has been chosen.

The controller transfer function is expressed in terms of formula:

$$W_{CC}(p) = k_{CC}\,\frac{CC \cdot p+1}{CC \cdot p},$$

where $T_{CC} = T_e = T_{reg}$ – time constant of the current controller;

$$CC = k_{reg}\,\frac{T \cdot R_e}{a_m\ T_{Tx} \cdot k_{Tx}}$$ – gain factor of the current controller;

k_{Tx} – current feedback ratio,

a_m – current loop optimization ratio according to modular optimum.

Transfer function of open current loop is given by:

$$OpenCL(p) = \frac{1}{a_m \cdot T_{\mu m} \cdot p \cdot (T_{\mu m} \cdot p+1)} \qquad (3)$$

Transfer function of closed current loop is given by:

$$Closed\ CL(p) = \frac{1/k_{Tx}}{a_m \cdot T_{\ m} \cdot p \cdot (T_{\mu m} \cdot p+1)+1} \qquad (4)$$

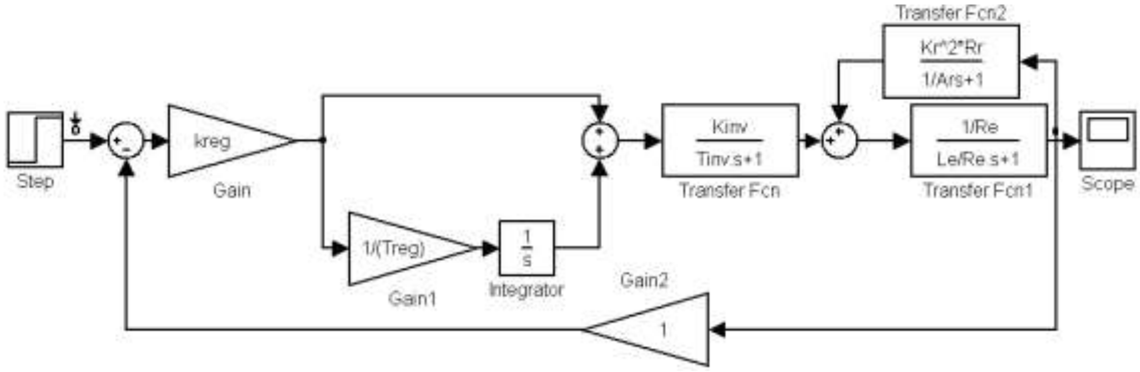

Figure 3. Current loop simulation model for stator current component i_{sx} control

Induction motor D09SA4 with following rated parameters is used for the electric drive simulation: Synchronous rotation speed $n_0 = 1500\,(\text{rpm})$, rated phase voltage $U = 220\,(V)$, rated motor power $P_{RAT} = 1.1\,(kW)$, rated slip $S = 0.067$, efficiency at rated power $\eta_{RAT} = 76.3\,(\%)$, power factor at rated power $\cos\phi_{RAT} = 0.78$, maximal-to-rated torque ratio $M_{MAX} / M_{RAT} = k_{\max}$ 2.7, starting-to-rated torque ratio $M_{ST} / M_{RAT} = k_{ST}$ 2.3, minimum-to-rated torque ratio $M_{MIN} / M_{RAT} = k_{MIN}$ 2.1, starting-to-rated current ratio $I_{ST} / I_{RAT} = k_i = 5.1$.

Result of the transient simulation in current loop, which is tuned on modular optimum, for step input signal $U_{REF} = 1$ (p.u.) working-off, is shown as transient characteristic i(t) in fig. 4.

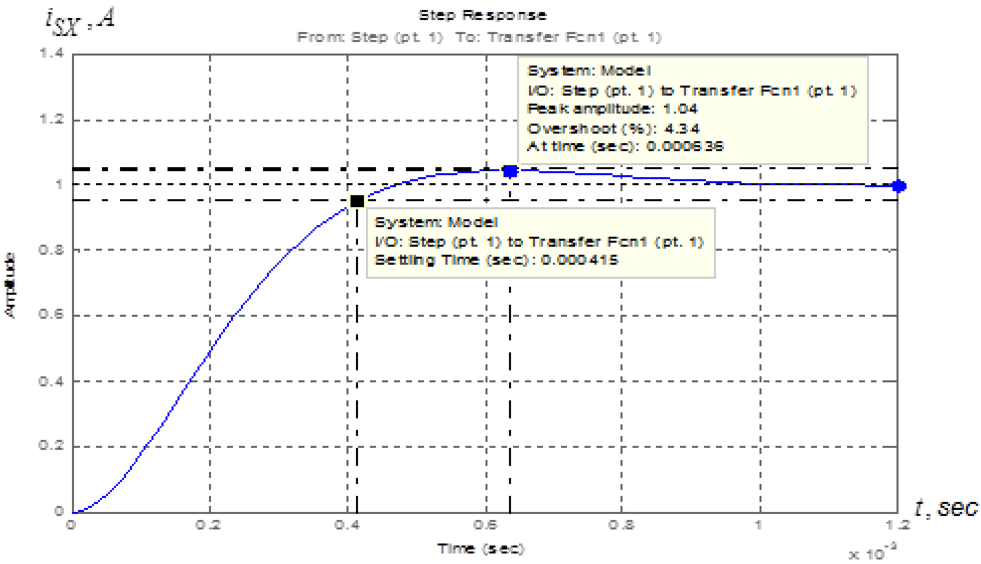

Figure 4. Current loop transient characteristic i(t)

Current loop quality factors are listed in table 1.

Table 1. Current loop dynamic quality factors

Factors	Expected	Obtained
Overshoot σ, %	4,32	4,34
$t_{RISE}^{(5)} = (\ )_{TR}$, p.u.	0,00041	0,000415
$\omega_{bw}^{(m)}, = \omega_{bw}^{(ph)},$, p.u.	7100	7120

Simulation results analysis shows that current loop tuning with PI-controller is close to second-degree system tuning on modular optimum. This loop is first-degree astatic system for control signal.

4. Flux-linkage loop optimization

Structure diagram of flux-linkage loop is shown in fig. 5.

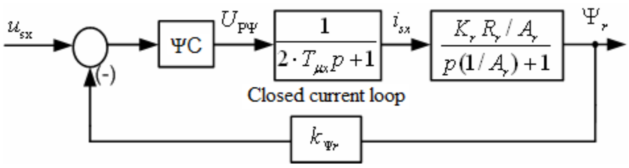

Figure 5. Structure diagram of flux-linkage loop

Considering the loop parameters a PI-controller is chosen. The controller transfer function is expressed in terms of formula:

$$W_{FLC}(p) = k_{FLC}\ \frac{FLC \cdot p+1}{FLC \cdot p}, \qquad (5)$$

where k_{FLC} – gain factor of the flux-linkage controller, $T_{FLC} = 1/A_R$ – time constant of the flux-linkage controller, Overall transfer function of open flux-linkage loop is given by:

$$Open\ FL(p) = \frac{1}{a_n \cdot a_m \cdot T_{\mu m} \cdot p \cdot \left(a_m \cdot T_{\mu m} \cdot p \cdot (T_{\mu m} \cdot p+1)+1\right)}$$

Overall transfer function of closed flux-linkage loop is given by

$$Closed\ FL(p) = \frac{1/k_{Fr}}{a_n \cdot a_m \cdot T_{\mu m} \cdot p \cdot \left(a_m \cdot T_{\mu m} \cdot p \cdot (T_{\mu m} \cdot p+1)+1\right)+}$$

From flux-linkage loop structure diagram (see fig. 5) a simulation model that is shown in fig. 6 can be built.

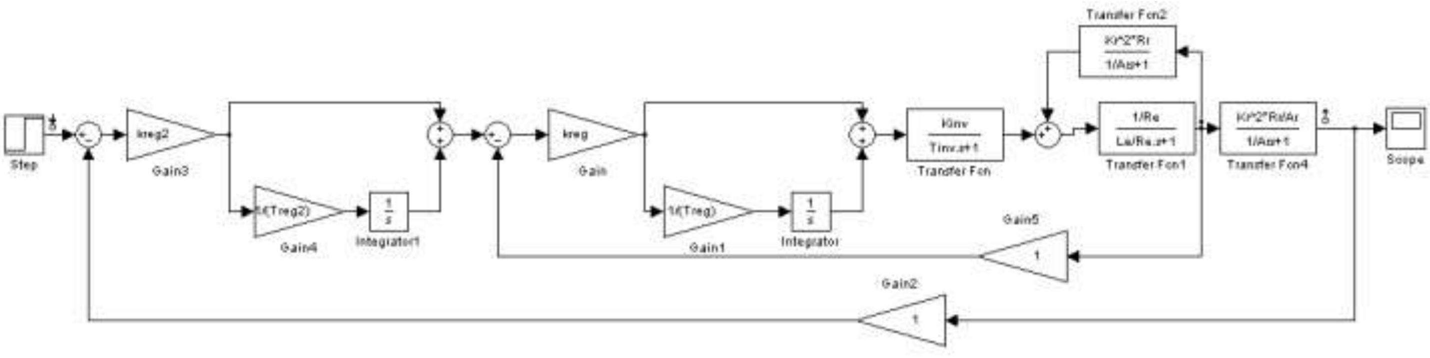

Figure 6. Flux-linkage loop simulation model

Results of the transients simulation in flux-linkage loop, which is tuned on modular optimum, for step input signal (V) working-off, are shown as transient characteristic □r (t) in fig. 7.

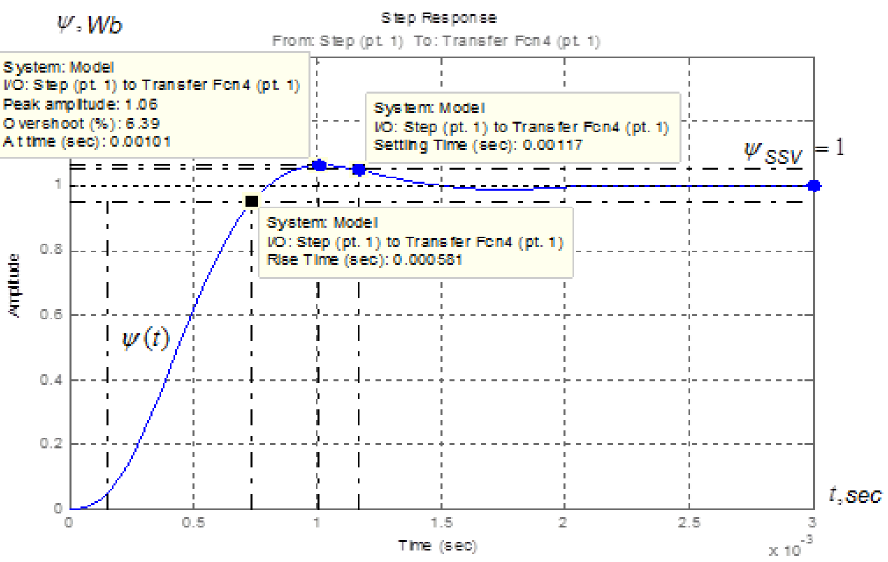

Figure 7. Flux-linkage loop transient characteristic

Quality factors of the flux-linkage loop operation are listed in table 2.

Table 2. Quality factors of closed flux-linkage loop

Factors	Expected	Obtained
Overshoot σ, %	8.14	6.39
$t_{\mathrm{RISE}}^{(5)}$, p.u.	0.0007	0.000581
$t_{\mathrm{TR}}^{(5)}$, p.u.	0.0012	0.00117
$\omega_{\mathrm{bw}}^{(m)}$, p.u.	5000	4640
$\omega_{\mathrm{bw}}^{(ph)}$, p.u.	3500	3440

Simulation results analysis of flux-linkage loop shows that results are close to expected flux-linkage loop quality factors. Small differences between current and flux-linkage quality factors are within acceptable limits of error.

5. Speed loop optimization

Structure diagram of speed loop is shown in fig. 8. Considering loop parameters a PI-controller is chosen. The controller transfer function is expressed in terms of formula:

$$W_{SC}(p)=k_{SC}\,\frac{SC\cdot p+1}{SC\cdot p}, \qquad (8)$$

where k_{SC} – gain factor of the speed controller;

a_c – speed loop optimization ratio according to symmetrical optimum [7, 8];

$T_{\mu c}=a_{\tau}\cdot T_{\mathrm{AVI}}$ (p.u.) – minor time constant of the loop;

$T_2=T_{SC}$ (p.u.) – major time constant of the loop.

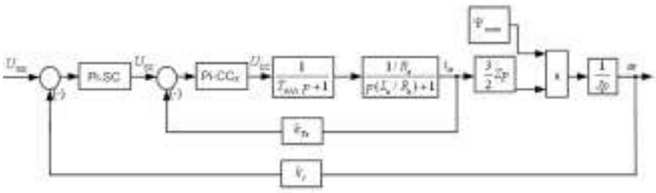

Figure 8. Structure diagram of speed loop tuned on symmetrical optimum

Transfer function of open speed loop, which is tuned on symmetrical optimum, is given by

$$Open\ SL(p)=\frac{b_c\cdot a_c\cdot a_m\cdot T_{\mu m}\cdot p+1}{b\ \cdot a_c\cdot a_m\cdot T_{\mu m}\cdot p\cdot\left(a_c\cdot a_m\cdot T_{\mu m}\cdot p\left(a_m\cdot T_{\mu m}\cdot p\cdot(T_{\mu m}\cdot p+1)+1\right)\right)}$$

Transfer function of closed speed loop without input filter is given by:

$$W_{Closed\ SL}^{without\ filter}(\ ) = \frac{\left(b_c \cdot a_c \cdot a_m \cdot T_{\mu} \quad \cdot \quad +1\right)}{b_c \cdot a_c \cdot a_m \cdot T_{\mu m} \cdot p \cdot \left(a_c \cdot a_m \cdot T_{\mu m} \cdot p\left(a_m \cdot T_{\mu m} \cdot p \cdot (T_{\mu m} \cdot p+1)+1\right)+1\right)+1}$$

Transfer function of closed speed loop with input filter is given by:

$$W_{Closed\ SL}^{with\ filter}(\ ) = \frac{1}{b_c \cdot a_c \cdot a_T \cdot T_{\mu m} p \cdot \left(a_c \cdot a_T \cdot T_{\mu m} \cdot p\left(a_m \cdot T_{\mu m} p \cdot (T_{\mu m} p+1)+1\right)+1\right)+1}$$

From structure diagram of the speed loop that is tuned on symmetrical optimum (see fig. 8) a simulation model is built, which is shown in fig. 9.

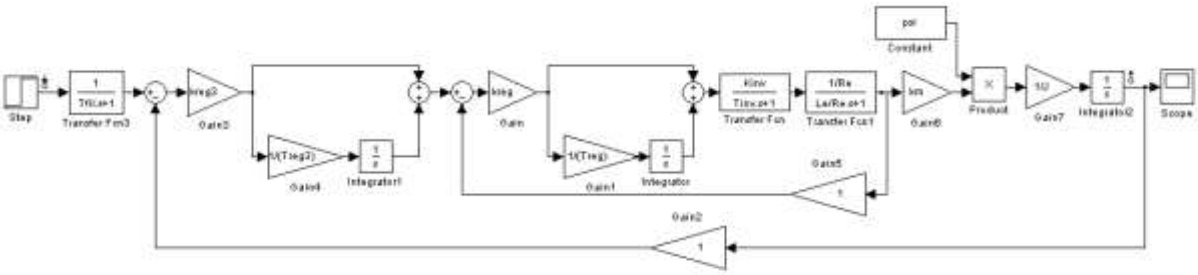

Figure 9. Simulation model of the speed loop that is tuned on symmetrical optimum

Transients simulation results in the speed loop, which is tuned on symmetrical optimum (with and without input filter) for step input signal $U_{REF} = 1$ (V) working-off, are shown as transient characteristic $\upsilon(t)$ in fig. 10.

Dynamic quality factors of closed speed loop with input filter are listed in table 3.

Table 3. Dynamic quality factors of closed speed loop with input filter

Factors	Without filter		With filter	
	Expected	Obtained	Expected	Obtained
σ,%	28.6	28.6	8.1	8.1
$t_{\mathrm{RISE}}^{(5)}$, p.u	0.0103	0.0105	0.023	0.023
$t_{\mathrm{TR}}^{(5)}$, p.u.	0.0314	0.036	0.033	0.046
$\omega_{\mathrm{bw}}^{(m)}$, p.u.	187.5	183	141.2	124
$\omega_{\mathrm{bw}}^{(ph)}$, p.u.	165.7	162	101.7	103

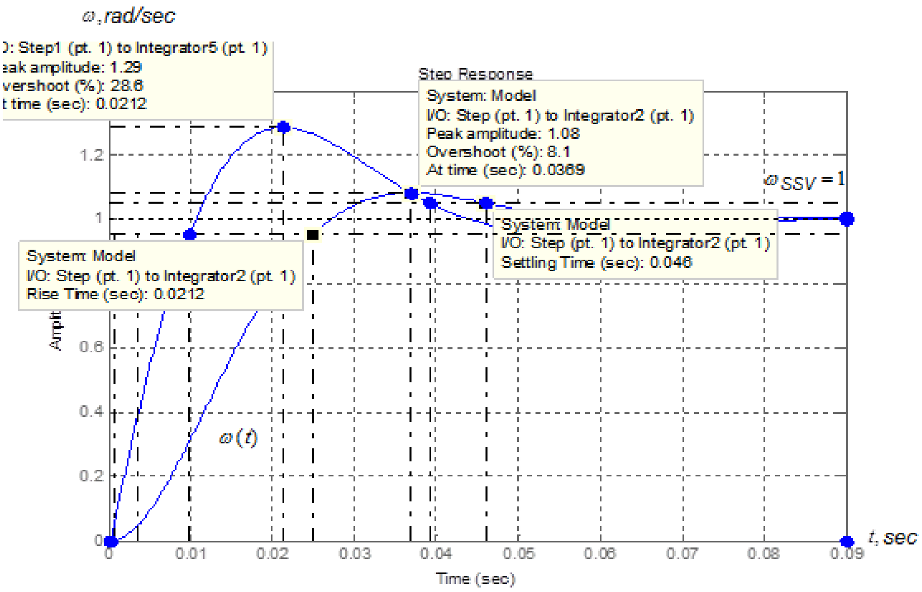

Figure 10. Transient characteristics $\upsilon(t)$ of speed loop that is tuned on symmetrical optimum

Conclusions and outlines

It has been found that application of variable frequency induction motor drive for flame reactor feed screw allows to provide dynamic quality factors comparable to the ones of DC electric drive based on shunt wound DC motor.

Analysis of dynamic quality factors of main loops of variable frequency induction motor drive system shows that the simulation factors are close to the expected ones. Minor error between them is caused by calculation simplifications during loop optimization. It should be noticed that transients quality factors in speed loop with input filter are better than without it.

Further studies of the flame reactor feeding system will be about determining the influence of the temperature and other environmental factors on performance of the electric drive, as well as their account in the control process.

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