Optimization of Filtering Properties of the Control System with the Smith Predictor

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Abstract: Centralized digital systems for control production processes use digital transfer channels for information management over Internet technology. These channels introduce additional problems in ensuring the sustainability of control systems with feedback. In the article is proposed to use Smith's predictor to compensate for temporary transport delays in the control of production processes. The authors give a mathematical model of the optimal structure of the digital control system and the principles of its design.

Key-Words: mathematical modeling, stabilization of systems by feedback, synthesis problems, feedback control, discrete-time systems, digital systems, optimal stochastic control.

1 Introduction

The modern control systems big productions use the distributed principles of control. The central controller sequentially performs functions of control of separate processes. Control data and information on a status of processes are transferred and accepted by means of network technologies. At the same time there is a temporal time delay in administrative process which breaks quality and stability of control

2 Problem Formulation

Figure 1 shows a simplified block diagram of a distributed control system with central control based on the Siemens Simatic S7-400 controller. The S7-400 controller is used as a regulator for a distributed process control system based on S7-300 controllers and PROFIBUS fieldbus [7]. The central controller, use PROFINET technology, provide and receives information about the status of the controlled process.

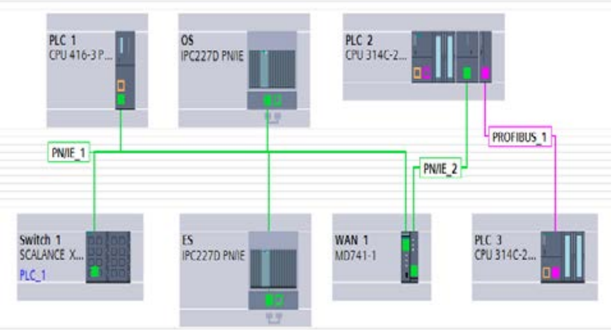

Fig 1. Typical structure of centralized control using the Siemens PCS 7 system elements.

In determining the stability and quality of regulation, it becomes necessary to consider:

1. Dynamic properties of control objects,
2. Dynamic properties of controllers,
3. Properties of the information transfer channels PROFIBUS and PROFINET,
4. Presence of noise signals when measuring the states of objects,
5. The presence of noise quantization and sampling as a result of digital processing of information,
6. Compensation for transport delays according providing of control information.

The solution of this problems is in optimizing the filtering properties of the control system by implementing the optimal configuration of the frequency response of the control system and using the prediction principles for constructing control regulators.

3 Problem Solution

The filtering properties of the control system are characterized by its ability not to miss the noise contained in the control action. The input of the control system receives not only useful signals, but also noise and interference. Interference is caused by random deviations of the control action, noise and errors in the measuring elements and other factors [5].

Interference and control arrive to different inputs of the system, but due to signals can be brought to the input of the control, we will assume in future that interference and control will always arrive at the input of the system.
Interference can be specified in the form of several time functions $\beta_p(t)$, but in most cases, the interference will have random characteristics, hereupon we will define their spectral density $S_p(\omega)$. Interference can cause additional changes in the output value, as a result of increasing the amount of error and reduce the quality of control.
The variance of the error of the control system caused by interference, which is a random function, is given by

$$\overrightarrow{\delta_p^2} = \frac{1}{\pi}\int_0^\infty S_p(\omega)[\Phi(j\omega)]^2\, d\omega, \quad (1)$$

Where $\Phi(j\omega)$ is the amplitude-phase frequency characteristic of a system with a closed loop.
In practice, when calculating the control system, there are often cases where the noise is specified in white noise format, whose spectral density can be expressed by the formula: $S_p(\omega) = c^2$. Then

$$\overrightarrow{\delta_p^2} = \frac{1}{\pi}\, c^2 \int_0^\infty [\Phi(j\omega)]^2\, d\omega, \quad (2)$$

From the preceding formula it follows that the value of the integral

$$I = \frac{1}{\pi}\int_0^\infty [\Phi(j\omega)]^2\, d\omega, \quad (3)$$

It can serve as a measure of filtering properties of the control system, the value of I being directly proportional to the mean square error caused by interference. Accordingly, the smaller the value of the desired integral, the better the filtering properties of the system.
The value of the integral

$$\tilde{I} = \frac{1}{\pi}\int_0^\infty [\omega^2\Phi(j\omega)]^2\, d\omega, \quad (4)$$

Can serve as an indicator of the power developed by the control system. When operating the control system, there are times when the root-mean-square error caused by interference does not exceed the permissible value, while the actuator's effective power is much higher than its nominal value. Which leads to an unacceptable load on the control system. Thus, the value of the integral I can also serve as an indicator of the quality of the control system.
The control system with respect to the control action is an astatic system of the first, second order, depending on the type of object and the type of regulator. Therefore, the low-frequency asymptote of the desired Bode diagram of the open control system has a slope of -20, -40, -60 dB/dek []. Asymptotes of the desired Bode diagram can be graphically divided into two parts: unchanged part and variable. The asymptotes of the Bode diagram of the control system elements that belong to the control object or cannot be changed belong to the unchanged part of the desired diagram. The variable part includes diagrams of Bode regulators and frequency correction elements (for example, sensor filters).
The position of the low-frequency asymptote belonging to the Bode diagram of the unchangeable part of the control system is determined by the value of the gain of the open system μ. Since the value of μ can only be found with allowance for the transfer function of the immutable part, the position of the low-frequency asymptote, which will be referred to below as the first low-frequency asymptote of the Bode diagram, will be determined separately for each case. In this case, the requirements for the component of the error caused by the perturbation applied to the control object must be taken into account.
The high-frequency part of the desired Bode diagram of the open control system is determined by the frequency response of the immovable part of the system. The high-frequency part of the Bode diagram of all considered types of control system elements can have the first asymptote with the second and third slope, the second asymptote with the fourth and fifth slope (Fig. 2)

The task of forming the desired Bode diagram of the open control system is reduced to determining the mid-frequency asymptote intersecting the frequency axis with the corresponding asymptotes of the Bode diagram of the unchanged part of the system. The point of intersection of the frequency axis by the Bode diagram is the cutoff frequency. The cutoff frequency determines the operating bandwidth (a bandwidth) of the control system and, together with the phase characteristic, makes it possible to evaluate its stability.
High-frequency asymptotes of the unchanged part mainly affect the stability of the internal loop of the control system and do not have a significant effect on the stability stocks of the system. Therefore, it becomes possible to use a filter in the control system to suppress high-frequency interference. The above asymptotes should be taken into account when analyzing the stability of the internal contour.
The position of the second low-frequency asymptote of the desired Bode diagram of the open control system can be determined from the predetermined accuracy of reproduction of the control system of the harmonic control component. The expression for the amplitude $\boldsymbol{\delta^a}$ of the harmonic component of the error of the control system in the case when the control action is characterized by the equality

$$(t) = \dot{\beta}_0 + \beta_a \sin \omega_p t \quad (5)$$

has the form:

$$\delta_a \approx |W\,(j\omega_p)|\beta_a\,. \quad (6)$$

Where: - β_a is the amplitude of the harmonic component of the control action.

The total greatest dynamic error in the absence of a perturbing moment

$$\delta = \beta_v + \beta_a = \frac{\dot{\beta}_0}{\mu} + \beta_a|W(j\omega_p)| \quad (7$$

Where: - β_v is the speed component of the error.
As desired, we use the characteristics obtained above. The formation of these characteristics is made taking into account the minimization of integrals I and $\tilde{I}$ and the provision of required reserves of stability.
In accordance with the above calculations, for the desired characteristic of the first series, we have:

$$\theta = \frac{p}{\omega_p} \quad (8)$$

$$W_1(\theta) = \frac{1}{\theta(0{,}63\theta + 1)[0{,}0625\theta^2 + 0{,}15\theta + 1]} \quad (9)$$

For the desired characteristic of the second type, we have:

$$W_2(\theta) = \frac{1{,}25\theta + 1}{\theta^2(0{,}25\theta + 1)[0{,}0256\theta^2 + 0{,}096\theta + 1]} \quad (10)$$

For the desired characteristic of the third type

$$W_3(\theta) = \frac{2{,}56\theta^2 + 1{,}6\theta + 1}{\theta^3(0{,}125\theta + 1)[0{,}0064\theta^2 + 0{,}048\theta + 1]} \quad (11)$$

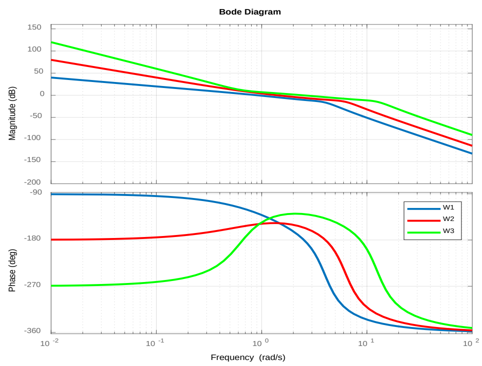

Fig. 2. The optimal form of the frequency response

Time delays are observed in industrial processes associated with transportation, mixing, burning of substances. They lead to the fact that information about the process provides to the regulator later than required, which can lead to instability of the closed-loop system. The complexity of managing objects with time delays is characterized by the ratio of the delay to the time constant of the object: the larger it is, the more difficult it is to achieve the required quality of regulation.
Increase the quality control of such objects can be done in two ways: by reducing the lag in the facility, by making constructive changes application of more complex structure of the control system, which allow to reduce negative influence of delay.

One of the structures intended for managing objects with delay,
is the Smith's predictor. It is recommended to apply it at the ratio of the delay to the time constant of the object, described by the following relation [1]:

$$\frac{\tau}{\tau + T} \geq (0.2 \dots 0.5) \qquad (15)$$

Where: - τ time delay, T - time constant of the object.
The block diagram of a closed automatic control system with Smith's predictor is shown in Fig. 3 [2, 4]. It contains an additional internal loop of feedback to the model block, which contains the model of the object with delay, as well as the model of the object without delay. An additional feedback loop generates a signal identical to that which will eventually appear at the output of the system, and feeds it to the regulator input until a signal from the main feedback loop appears. As it increases, the signal from the output of the model unit decreases.

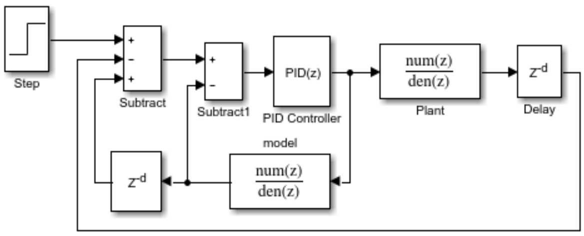

Fig.3 Structural diagram of a closed automatic control system with Smith's predictor

The optimal form of the desired frequency characteristics (9), (11), (13) leads us to find the optimal form of the Bode regulators:

$$W_{1R}(s) = 0{,}25 + \frac{\omega_p}{s} \qquad (16)$$

$$W_{2R}(s) = 1{,}25 + \frac{\omega_p}{s} \qquad (17)$$

$$W_{3R}(s) = 1{,}6 + \frac{\omega_p}{s} + \frac{2{,}56 \cdot s}{\omega_p} \qquad (18)$$

The central processor of a distributed control system, when performing the function of the controller of a large number of objects, introduces a time delay in the calculation of the control signals. With a large congestion of signal transfer channels, there is also an additional time delay. Therefore, it becomes necessary to take into account the additional time delay when setting up Smith's predictor. The problem of setting the predictor is complicated by the random nature of the additional time delay.
To study the effect of a random additional time delay on the quality of regulation and the development of a technique for predicting the predictor, a distributed control system model was developed. The model is implemented with the help of Simulink Matlab (fig.4) and contains elements that simulate nonlinearities, discreteness of information processing, random nature of measurement noise and time delays.

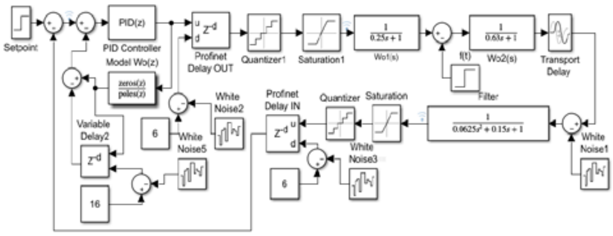

Fig.4. Model of the distribution control system

The Smith Predictor has a high sensitivity to change parameters, time delay of the object and information transfer channel. Therefore, it is necessary to find the principle of adjusting the time delay parameters of the model, which would take into account the random nature of the delay in transferring information over the PROFINET network.
In the above model, the random nature of the information transfer delay over the network was simulated by a digital spectrum generator with a limited frequency spectrum (The Band-Limited White Noise).
The results of the simulation in the form of transient characteristics are shown in the fig. 5a, 5b, 5c, 5d.
The transitional characteristic of a control system at optimum control of system, which doesn't contain temporary delay, is provided on the figure 5a. The transitional characteristic of a control system in the presence of temporary delay $\tau = 4T_0$ with exact control of a predictor of Smith is provided on the figure 5b. Smith's predictor allows to keep quality of control at increase in the period of sampling.
The figure 5c shows deterioration quality of control because of emergence of an additional casual temporary delay at transfer of information on channels of PROFINET network. The casual temporary delay is modelled by the software Simulink module The Band Limited White Noise.

Simulink software simulate the effect of white noise by using a random sequence with a correlation time much smaller than the shortest time constant of the system. The Band-Limited White Noise block produces such a sequence. The correlation time of the noise is the sample rate of the block. For accurate simulations, use a correlation time much smaller than the fastest dynamics of the system. You can get good results by specifying

$$t_c = \frac{1}{100} \cdot \frac{2\pi}{f_{max}} . \quad (19)$$

Where: - f_{max} is the bandwidth of the system in rad/sec.

In case of simulation sampling rate of model of management system is accepted to the maximum frequency of f_{max}. We accept that the random variable of a time delay has the discontinuous uniform distribution, that is

$$P(X = x_i) = \frac{1}{n}, \qquad i = 1, \ldots, n \quad (20)$$

Then its mathematical expectation is equal to an arithmetic average of all accepted values

$$M[X] = \frac{1}{n} \sum_{i=1}^{n} x_i . \quad (21)$$

In fig. 5d the quality of control of system is regenerated by account in setup of the regulator of Smith mathematical waiting of an accidental component.

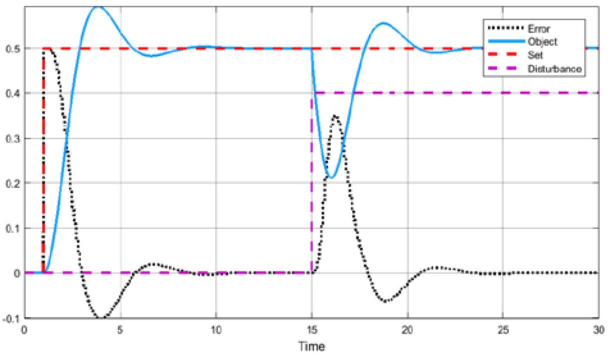

Fig.5a The step response of a control system (the object without delay)

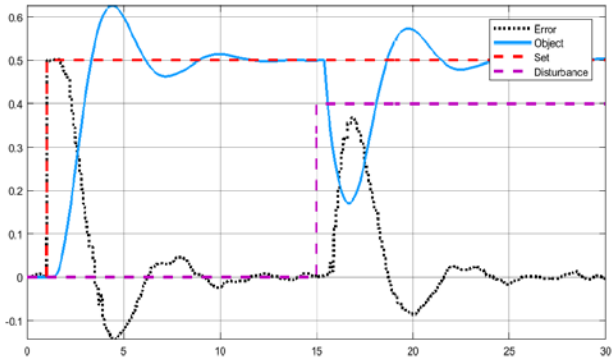

Fig.5b The step response of a control system (the object with delay $\tau = 4T_0$)

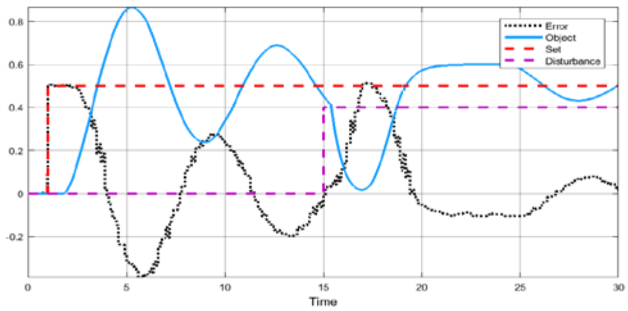

Fig.5c The step response of a control system (object with delay $\tau = 4T_0$ and network delay as mathematical expectation M=2)

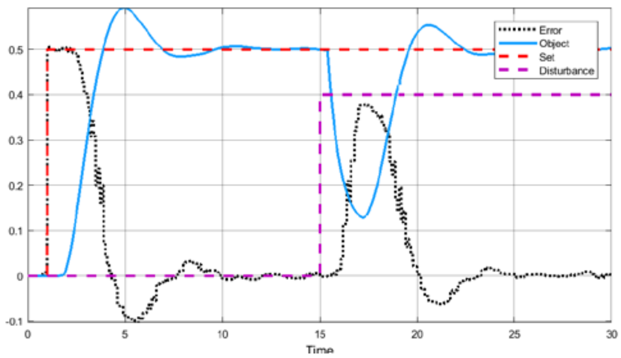

Fig.5c The step response of a control system (the object with delay$\tau = 4T_0$ and network delay as mathematical expectation M=2 after configuration of Smith's predictor)

4 Conclusion

This paper proposes a method for choosing optimal frequency response taking into account minimization of energy costs. This allowed to unify the regulator configuration $\omega(p)$ was replaced with the required control object. A mathematical model of the Smith's predictor was proposed, which allows to compensate not only the delay of the object, but also the delay of the network. With the help of the distributed control system model, it is shown that if the delay is a random nature during the providing through the network, it can be considered as white noise. The Smith predictor must be set to the total delay time and the mathematical expectation of the network. Such a control principle can increase the number of control objects within the same cycle of work of the PCS7 system interruption while maintaining the quality of control.

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