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Comparison of the Model and the Experiment of Synchronizing Two Shafts with a PID Controller Using Incremental Encoders and Frequency Converters

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The authors declare that there is no conflict of interest.

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Abstract. The precise synchronization of the main drive shaft and the driven shaft of a screw conveyor is a critical industrial task, upon which the overall operability of the screw conveyor depends, as well as the maintenance of the drive shafts, sprockets, and belt in a functional state. This study presents a comparative analysis of the experimental application and simulation results of a PID controller for synchronizing the rotation of two shafts using incremental encoders and frequency converters. Modern methods of automated control systems are adopted as the methodological basis of the research, including the adjustment of parameters for frequency converters and PID controllers, and the digital processing of encoder signals. The objective of the study is to compare the accuracy and dynamic characteristics obtained during the simulation phase with the results obtained from the real system. The research task is to develop a mathematical model of the system, tune optimal PID controller parameters for both the mathematical model and the real system, and analyze the resulting discrepancies between the data, identifying their causes. As a result of the study, a mathematical model of the synchronization system was developed, optimal PID controller parameters were determined, the main factors causing discrepancies between simulation and the real system operation were analyzed, and recommendations were formulated to improve its accuracy.

Keywords: position feedback, variable-frequency drive, simulation modeling, transient process, automated control systems

Authors' contribution

Kukharskii M.I. — writing the source text, developing a mathematical model, and commissioning; *Zhuravlev A.O.* — analysis of scientific literature, recommendations; *Andrikov D.A.* — scientific management, research concept. All authors read and approved the final version of the article.

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Сравнение модели и эксперимента синхронизации двух валов ПИД-регулятором с инкрементальными энкодерами и преобразователями частоты

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Заявление об использовании технологий искусственного интеллекта

При создании настоящей статьи технологии генеративного искусственного интеллекта не использовались.

Заявление о доступности данных

Все данные, полученные в ходе этого исследования, включены в опубликованную статью.

Аннотация. Точная синхронизация вала основного двигателя и вала приводного языка спирального транспортера является важной задачей в промышленности, где от нее зависит работоспособность спирального транспортера в целом, а также сохранение приводных валов, звезд и ленты в работоспособном состоянии. Представлен сравнительный анализ экспериментального применения и результатов моделирования ПИД-регулятора для синхронизации вращения двух валов с использованием инкрементальных энкодеров и управляемых преобразователями частоты. В качестве методологической базы исследования использованы современные методы управления автоматизированных систем управления, включая настройку параметров преобразователей частоты и ПИД-регулятора и цифровую обработку сигналов энкодеров. Цель исследования — провести сопоставление точности и динамических характеристик, полученных на этапе моделирования, с результатами, полученными на реальной системе. Задача исследования — разработать математическую модель системы, настроить оптимальные параметры ПИД-регулятора как для математической модели, так и для реальной системы и изучить полученные расхождения между данными, выявив их причины. По итогам исследования разработана математическая модель системы синхронизации, определены оптимальные параметры ПИД-регулятора, проанализированы основные факторы, вызывающие расхождения между симуляцией и реальной работой системы, и сформулированы рекомендации для повышения ее точности.

Ключевые слова: обратная связь по положению, частотно-регулируемый привод, имитационное моделирование, переходный процесс, автоматизированные системы управления

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Introduction

Modern advances in automatic control theory, modern control systems, and digital technologies are actively promoting the automation of industrial processes. One of the key challenges in this area is

ensuring precise synchronization of moving parts in complex process equipment. This includes some spiral conveyors, complexity of which stems from design features and dimensional requirements, necessitating a second gear motor. Experience with such systems shows that even minor errors can

lead to serious consequences for both the equipment manufacturer and the customer.

The relevance of this topic and the demand for technological solutions stem from the challenges inherent in the design and operation of such systems. Engineering errors associated with incorrect assessment of nonlinearities, disturbances, or dynamic characteristics lead to reduced equipment efficiency and shorten its service life. To avoid significant time and material costs, it is necessary to develop a formalized mathematical model for determining the parameters and configuration of the shaft synchronization system. This model will serve as the basis for subsequent implementation and testing on real equipment. PID controllers, whose methods have proven their effectiveness, are widely used in automation. To solve the given synchronization problem, careful tuning of the PID controller parameters is necessary [1; 2]. Modern digital technologies, such as programmable logic controllers (PLCs), allow for the tuning of data on physical processes and controllers virtually and with minimal latency, minimizing the time spent on experiments on real equipment [3].

In modern industry, approximately 95% of control loops use PID control technology [4]. In Japan, the use of PID control has reached 85.4% [5], and this figure continues to grow every year. In 2002, Desborough and Miller conducted a study that showed that in the United States there are more than 11,600 controllers with PID control structures used in various industrial processes, with more than 97% of feedback loops using a PID control algorithm [6]. The purpose of the study is to conduct a comparative analysis of the obtained results of modeling and launching real equipment using PID control for synchronizing two drive shafts using incremental encoders and frequency converters, as well as to formulate recommendations for improving the accuracy and stability of the synchronization system.

1. Theoretical Background

This section describes the theoretical principles underlying the system under consideration. It describes the concepts of synchronizing rotating

shafts, the operating principle and design of measuring sensors and frequency converters, and the operating algorithm used to achieve synchronous shaft rotation.

Shaft synchronization involves maintaining a given relationship between their angular velocities or angular positions. Synchronization by angular velocity requires the angular velocities of rotating shafts to be identical or proportional, and is used to ensure a constant relative position of the mechanical component. Synchronization by angular position requires maintaining a constant difference in angular positions, and is used for precise positioning of the mechanical component. This paper addresses the problem of maintaining a zero difference in the angular velocities of rotating shafts:

$$\omega_1 - \omega_2 = 0, \quad (1)$$

where ω_1, ω_2 is angular speeds of shafts, rpm.

To maintain this relationship under external disturbances, such as changing loads or friction, an automated control system is required to adjust the speed of the driven shaft, in this case the drive shaft.

One of the most common sensors used to determine angular position and measure rotational speed is the incremental encoder. Its operating principle is based on converting mechanical rotation into a sequence of electrical signals [7].

The incremental encoder generates two main signals, A and B, and a zero signal, Z. Signals A and B are identical in frequency but are offset relative to each other by one-quarter of a period [8]. This offset allows the direction of shaft rotation to be determined, and pulse counting determines the angular velocity. Signal Z generates one pulse for each complete shaft revolution.

The system under consideration will utilize two incremental encoders with a 100-pulse-per-revolution rate, each with A and B signals. This requires four high-frequency inputs. The system will utilize a Siemens S7-1214 PLC, whose first six discrete inputs are high-frequency, with a range of up to 100 kHz. The encoder-PLC connection diagram is shown in Figure 1.

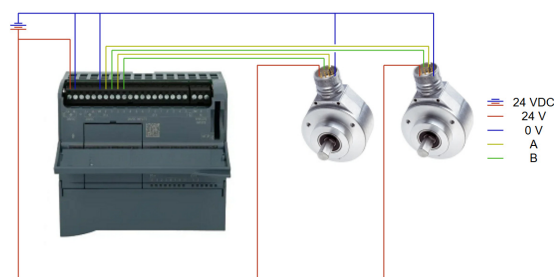


Figure 1. Connection diagram of the encoders to the PLC
Source: by M.I. Kukharskii.

Frequency converters are used to control asynchronous motors using a PLC. They are used to engage and regulate speed. In the system under consideration, gearmotors are controlled using scalar control (U/f), a method that maintains a constant voltage-to-frequency ratio. The motor shaft speed is estimated based on the frequency of the voltage across its windings [9].

One of the functions of frequency converters is soft starting — gradually increasing and decreasing the frequency. For the driving shaft, the ramp-up time is 5 seconds, and the ramp-down time is 7 seconds. For the driven shaft, the ramp-up and ramp-down time is 1 second. Slow acceleration and deceleration of the driving shaft are required for smooth operation, while the driven shaft must have high response speed to quickly reduce the desynchronization value to zero.

Communication between the PLC and frequency converters will occur using the industrial RS-485 Modbus RTU communication protocol [10]. To ensure rapid change of the setpoint (speed reference) of the frequency converter on the driven shaft, a pulse input must be used. In the Siemens S7-1214 PLC, the first four discrete outputs are pulse outputs. Rapid startup and shutdown of each frequency converter is also required. The connection diagram for the Danfoss FC51 frequency converters and the PLC is shown in Figure 2.

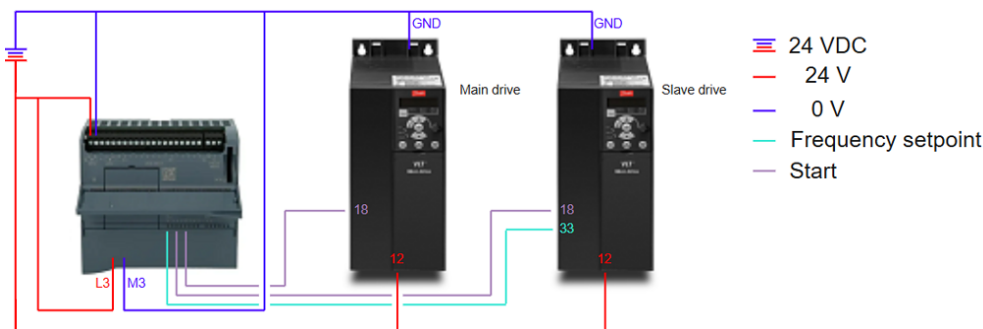


Figure 2. Connection diagram of the frequency converter to the PLC
Source: by M.I. Kukharskii.

The PID controller is a feedback algorithm in automatic control theory, widely used in industrial automation. It is designed to minimize the error between the actual value and the desired one (setpoint). This algorithm calculates the control action using three components: the proportional component (P) — the greater the error, the greater the proportional contribution; the integral component (I) — eliminates the steady-state error, accumulating it over time; the differential component (D) — predicts the future error, reduces overshoot and oscillations [11, pp. 64–70].

The Tia Portal V17 software is used for the Siemens PLC program. This software contains a large number of built-in libraries, including the PID controller in the PID_Compact function [12]. The controller will be tuned manually using an iterative method by changing the following parameters of the process object: K_P — proportional coefficient; T_I — integration time; T_D — differentiation time; prop_weight — proportional component weight; sampling_time — control action calculation frequency. The combination of the high performance of the S7-1200 series PLC,

the rapid adjustment of PID controller parameters in real time, and the empirical approach will allow for the rapid and accurate determination of optimal controller coefficients for the mathematical model, significantly reducing the time it takes to commission a real system.

2. Implementation and Testing of a Mathematical Model in the Tia Portal V17 Environment

The mathematical model for synchronizing two shafts is based on the characteristics of real equipment, namely, the motor nameplates and gear ratios of the gearboxes specified by the manufacturers of this equipment. The shaft speed of the driven motor is 900 rpm at 50 Hz, the gearbox ratio is 40. The shaft speed of the leading motor is 1400 rpm, the gearbox ratio is 8.98. However, this spiral conveyor is designed in such a way that the leading motor drives the cardan system, and the cardan drives the belt itself. Therefore, for the leading motor, it is necessary to take into account the gearbox ratio of the cardan, which is 7.97. To find the number of shaft revolutions that set the spiral conveyor in motion at a speed of 50 Hz, it is necessary to use formulas (2) [13]:

$$N_{\text{shaft}} = \frac{N_{\text{motor}}}{N_{\text{gear ratio}} \cdot N_{\text{cardan}}}, \quad N_{\text{cardan}} > 0;$$

$$N_{\text{shaft}} = \frac{N_{\text{motor}}}{N_{\text{gear ratio}}}, \quad N_{\text{cardan}} = 0. \quad (2)$$

Substituting the motor and gearbox parameters into expression (2), we obtain the following data: leading motor shaft speed 19.56 rpm, driven motor shaft speed 22.5 rpm.

The mathematical model assumes a linear relationship between shaft speed and frequency converter frequency.

The calculation of the number of shaft revolutions is performed in a cyclic interrupt block with an execution period of $T = 10$ ms. This requirement is due to the need for a constant time between calculations, which is a prerequisite for minimizing errors for the correct operation of the

system as a whole. The number of revolutions is calculated using the formula

$$N[k] = N[k-1] + \Delta N, \quad (3)$$

where ΔN — shaft increment per 10 ms.

As the increment time increases, the error begins to enlarge, leading to a decrease in the accuracy of the instantaneous shaft position. To calculate the ΔN increment, the current shaft speed, measured in rpm, is used:

$$\Delta N = \frac{N_{\text{shaft}}}{60 \cdot 100}. \quad (4)$$

Formula (4) represents the fraction of a revolution completed by the shaft in 10 ms, which is accumulated in the counter, forming the precise absolute shaft position.

Incremental encoders have a resolution of 100 pulses per revolution. The conversion of the absolute shaft position into an encoder pulse counter occurs according to the expression

$$N[k]_{\text{encoder}} = N[k]_{\text{shaft}} \cdot 100. \quad (5)$$

The resulting integer value for the number of pulses $N[k]_{\text{ЭИК}}$ allows for a highly accurate simulation of the signals that a real encoder would generate with output signals A and B . These signals and the total number of pulses are necessary for the synchronization algorithm to operate.

Smooth start and stop are standard features of modern frequency converters. These functions reduce dynamic loads on mechanical components and eliminate sudden speed jumps. Incorporating these characteristics into the mathematical model is necessary for evaluating dynamic processes close to practical ones, as well as for correctly tuning the PID controller.

To simulate these functions, a model of output frequency changes was developed. The algorithm is implemented in a cyclic interrupt block with an execution period of $T = 10$ ms. The model is based on the assumption that the time to reach a set speed is linearly dependent on its magnitude. The set acceleration time corresponds to the time it takes to reach maximum speed from zero; to reach an

arbitrary set speed, the time required is directly proportional to the ratio of the set speed to the maximum speed.

The speed increment over a 10 ms time is calculated using the following formula:

$$\Delta f = \frac{100}{t \cdot 100} = \frac{1}{t}, \quad (6)$$

where t — specified acceleration/deceleration time.

To solve the problem of synchronizing two rotating shafts, a function block from the built-in “PID_Compact” library was used in the TIA Portal development environment. “PID_Compact” is an optimized implementation of a PID controller adapted for Siemens PLCs and includes the necessary functions for stable operation.

The “PID_Compact” process object was configured by adjusting the following parameters: K_P — proportional coefficient value; T_I — integration time; T_D — differentiation time; prop_weight — proportional component weight; sampling_time — PID controller algorithm calculation time.

2.1. Tuning using the CHR method

To tune the PID controller parameters using the Chin-Hrones-Reswick method, it is necessary

to determine the delay time L and the equalization time T [14].

The desired transient response curve is shown in Figure 3.

In this system, the sampling_time parameter is always equal to 0.1 s, and the speed increases linearly, so the delay time is equal to this parameter.

Based on the readings in graph 3, with a step effect of 40%, this time is equal to 0.152 s.

To calculate the PID controller parameters, use the formulas presented in Table 1 [15].

Table 1. Formulas for calculating PID controller parameters using the CHR method

K_p	T_i	T_d
$0,95 \times T/L$	$2,4 \times L$	$0,42 \times L$

Source: by M.I. Kukharskii.

PID controller parameters: $K_p = 1.444$, $T_i = 0.24$, $T_d = 0.042$; the transient process is shown in Figure 4.

The CHR method showed unsatisfactory control quality: the control time, approximately equal to 60 s, as well as significant overshoot, require manual fine-tuning of the PID controller parameters.

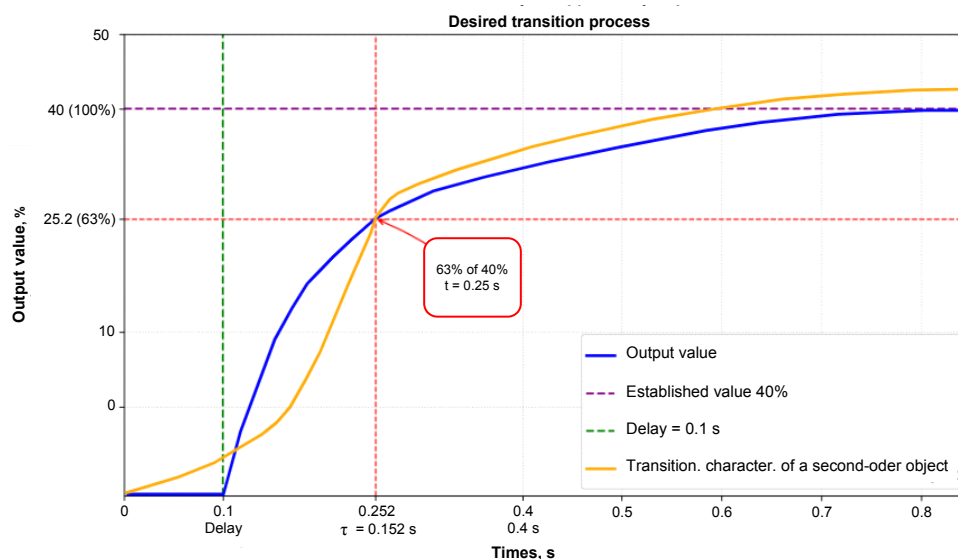


Figure 3. Desired transition process

Source: by M.I. Kukharskii.

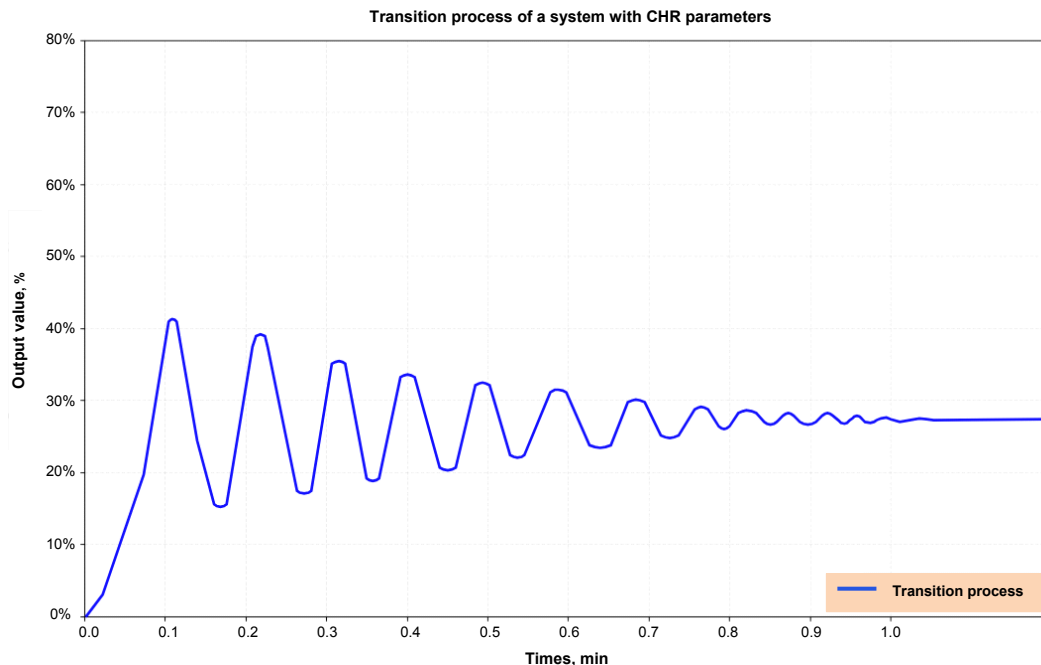


Figure 4. Transient process of the PID controller of the mathematical model with parameters of the CHR method
Source: by M.I. Kukharskii.

2.2. Setting up using an Empirical Iterative Method

The tuning involved selecting optimal parameters with visual inspection of the transient response of the implemented mathematical model.

At the initial stage, the K_P parameter was adjusted with the integral and differential components disabled, resulting in a value of 9.7. This proportional value is necessary to ensure a strong control value even with small desynchronization values.

The second step in tuning the controller was introducing an integral component, T_I , equal to 1 s. This value allows for the accumulation of the corrective action necessary to compensate for disturbances without causing a slowdown in the transient process.

The next step was adjusting the differential component to suppress oscillations, $T_D = 0.1$. With a given differential component value, the system demonstrates overall stability.

The fourth step was selecting the proportional component weight, $\text{prop_weight} = 0.3$. This con-

figuration is necessary to reduce the abruptness of the response to a jump in the speed reference and ensure smooth operation.

The `sampling_time` parameter is set to 0.1 to ensure tight coupling to the main program execution loop.

The transient process is shown in Figure 5.

The control time is 5.5 seconds, which meets the requirements of the task, taking into account the system's inertia. The resulting overshoot value of 7% is optimal for industrial systems. Minor damped oscillations of 3–4% are also present before the control time expires. The desynchronization value did not exceed 3, and after the control time expired after system startup, it became static and equal to zero.

The resulting parameter configuration meets the requirements for speed, stability, and smooth operation of the slave frequency converter, taking into account its dynamic properties. These PID controller parameters, obtained using the mathematical model, will form the basis for implementing synchronization in the real system.

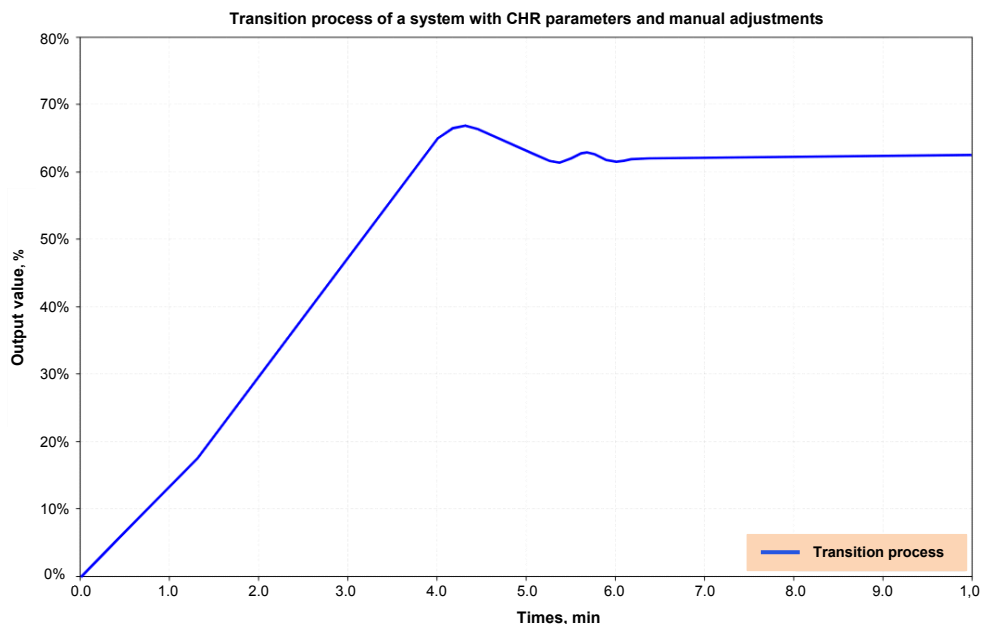


Figure 5. Transient process of the PID controller of the mathematical model with parameters of the empirical method
Source: by M.I. Kukharskii.

3. Implementation and Testing of a Real System

3.1. Commissioning Works

The PID controller parameters obtained from the mathematical model were integrated into the real system. However, unaccounted for nonlinear-

arities, such as soft stop and start, as well as actuator errors, resulted in system oscillations without a steady-state value.

Empirical tuning yielded the final PID controller parameters: $K_P = 6$; $T_D = 0.195$. The transient process is shown in Figure 6.

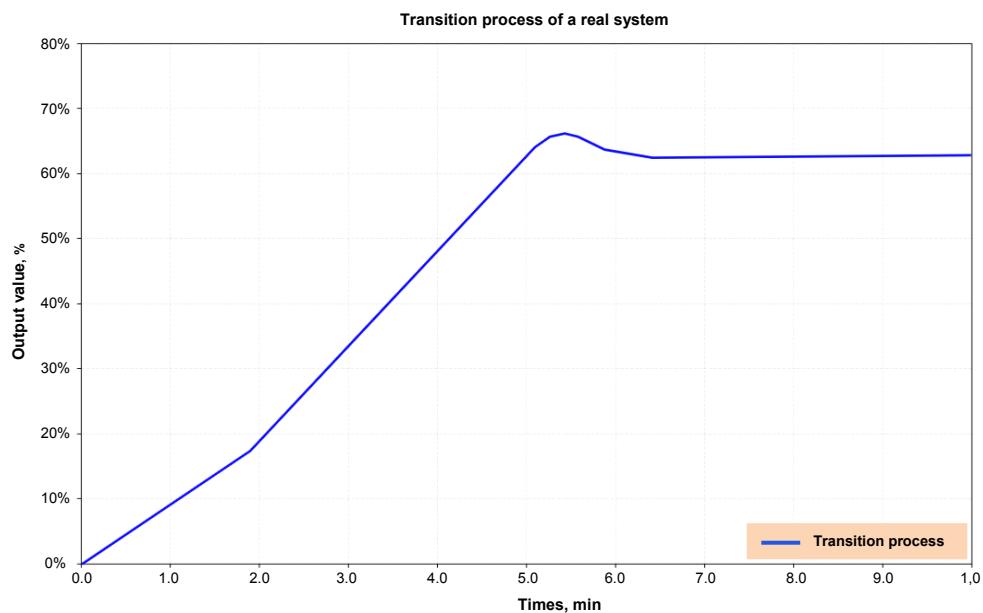


Figure 6. Transient process of a PID controller for a real system
Source: by M.I. Kukharskii.

As a result, the integral component retained its previous value, and despite a slight increase in the control time to 7 seconds, it is acceptable for this process, taking into account the 7-second soft start of the drive shaft. Overshoot decreased to 6%, and the increase in the differentiation time reduced the amplitude of the damped oscillations to 2%. The desynchronization value did not exceed 2, and after the control time had elapsed after system startup, it became static and equal to zero.

The system demonstrates smooth and stable transient processes, confirming its readiness for operation in the industrial setting.

3.2. Recommendations for Accuracy Improvement

In order to improve the accuracy of the synchronization system, it is advisable to replace existing encoders with 100 pulses per revolution (PPR) characteristics with encoders with a higher pulse count (500, 1000), which will reduce the position error of the driven shaft [16].

Special attention should be paid to the hardware — replacing frequency converters with servo drives and using encoders integrated into the servo drives. It is important to note that servo drives control not only the shaft speed but also the precise angular position of the rotor, which ensures greater dynamics and rigidity [17]. Servo drives allow for instantaneous response to disturbances and maintain precise phase relationship between the shafts [18–19].

4. Comparative Analysis of the Dynamic Characteristics of a Real System and a Mathematical Model

The transition from the mathematical model to the real system required adjustments to the PID controller, which affected the system's dynamic characteristics. A comparative analysis is presented in Table 2.

The need to reduce the proportional component indicates a higher sensitivity of the real system than predicted by the mathematical model. This is due to the presence of nonlinearities in the real system, arising from friction, backlash, and nonlinearities in smooth starting and stopping.

Table 2. Comparison of parameters

Parameter	Mathematical model	Real system
K _P	9.7	6
T _D , c	0.1	0.195
Regulation time, s	5.5	7
Overshoot, %	7	6
The amplitude of the oscillations, %	3–4	≤2

Source: by M.I. Kukharskii.

The real system contains additional delays, such as shaft stiffness during rotation and signal processing delays in the frequency converter. To compensate for these, the differentiation time was significantly increased by almost 2 times.

After adjusting the parameters, the control time increased by 1.5 seconds to 7 seconds, while reducing the overshoot to 6%. The increase in control time remains within the technological limits of the drive shaft acceleration process, without negatively affecting the process.

A direct consequence of increasing the differentiation time is a reduction in oscillation amplitude from 3–4% to 2%, indicating increased system stability.

Adjusting the PID controller parameters is a natural and mandatory requirement when transitioning from a mathematical model to a real system. The final parameters should be considered optimal for the given operating conditions due to the system demonstrating a shaft desynchronization value equal to zero, acceptable speed of response and high stability corresponding to the requirements of the synchronization process of two shafts of a spiral conveyor.

Conclusion

The study successfully developed a mathematical model and launched a real-world synchronization system for two spiral conveyor shafts based on a Siemens S7-1214 programmable logic controller. Transitioning from the mathematical model to practical implementation enabled the creation of a robust control system that meets the requirements of real-world operating conditions.

The transient response graph confirms the controller's effectiveness: the control time does

not exceed the drive shaft's acceleration time, and overshoot does not exceed 7%. The practical significance of this work lies in the development of a methodology for adapting the mathematical model under ideal conditions to real-world industrial equipment, taking into account its nonlinearities and errors.

Prospects for further research include expanding the functionality to a system with a larger number of shafts and optimizing the system for operation with variable loads. Further development of the synchronization system involves implementing recommendations for replacing frequency converters and separate encoders with servo drives with integrated encoders capable of delivering a higher number of pulses per shaft revolution. The system presented in this study can be successfully implemented in related areas of industrial automation that require synchronization of rotational movements.

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