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Hidrolik oransal valf sisteminde farklı PLC serilerinin PID kontrol performanslarının karşılaştırılması-Deneysel bir kurulum

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Comparison of PID Control Performances of Different PLC Series in a Hydraulic Proportional Valve System-An Experimental Setup

Highlights

- *Comparison of PID control performances of different PLCs*
- *Using a real-physical system*
- *Hydraulic proportional valve system implementation*
- *Detailed experiments and analysis*
- *PLC suggestion based on experiments and analysis results*

Graphical Abstract

This study compares the operational performances of S7-300, S7-400, S7-1200 and S7-1500 series PLCs with four different CPUs for the hydraulic proportional valve control system in P, PI, PD and PID control modes in Kardemir Inc. Rail and Profile Rolling Mill

Table 7. The best control results of all PLCs

PLC and Control Mode	S7-300	S7-400	S7-1200	S7-1500
	PI (K_p=5, K_i=1)	PI (K_p=5, K_i=1)	PI	PID
Initial Position (mm)	3.91	1.42	1.41	1.39
Set Position (mm)	100	100	100	100
10% Position Value (mm)	13.51	11.27	11.269	11.25
90% Position Value (mm)	90.39	90.14	90.141	90.13
Rising Time (s) (10%-90%)	4.31	4.13	4.47	7.3
0% Position Value (mm)	3.91	1.42	1.41	1.39
50% Position Value (mm)	51.96	50.71	50.705	50.69
Delay Time (s) (0%-50%)	3	2.64	4.92	4.7
Maximum Overshoot (mm)	8.9	6.9	0.41	0.62
Maximum Undershoot (mm)	4.3	1.9	0.04	0.2
Settling Time (s)	18.4	19.2	10.4	8.9

Figure. Hydraulic proportional valve and Experimental setup installed with S7-300 PLC

Aim

Comparison of PID control performances of different PLCs.

Design & Methodology

For PID control of a real hydraulic proportional valve system, the performances of different series PLCs were evaluated by obtaining data via the SCADA / IBA system.

Originality

Comparing and analyzing the PID control performances of different PLCs in a real hydraulic proportional valve system based on data taken from the real SCADA/IBA system.

Findings

It can be seen from the experimental results that the Pre-Tuning and Fine-Tuning features in the S7-1200 and S7-1500 series PLCs, which are the new generation PLCs as compared to the S7-300 and S7-400 PLCs, provide better results than manual parameter adjustment.

Conclusion

It is observed that PI control gives better results for the S7-1200 series PLC and PID control gives better results for the S7-1500 series PLC in the system established for the study. Among all PLCs, the best result in terms of settling time was obtained in the S7-1500 series PLC.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Comparison of PID Control Performances of Different PLC Series in a Hydraulic Proportional Valve System-An Experimental Setup

Research Article

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ABSTRACT

The significance of both cost and production speed has gained importance within the industrial sector. During the installation of industrial facilities, selection of materials with ideal properties is crucial for achieving the required system performance. Especially, when working with moving equipment, the speed required by the system as well as the costs of the necessary equipment are taken into account. This study compares the operational performances of S7-300, S7-400, S7-1200 and S7-1500 series PLCs with four different CPUs for the hydraulic proportional valve control system in P, PI, PD and PID control modes in Kardemir Inc. Rail and Profile Rolling Mill. Performance comparisons were made based on settling time, rise time, delay time and positive and negative maximum overshoots. For S7-300, S7-400, S7-1200 and S7-1500 series PLCs, minumum settling time values were 18.4 s, 19.2 s, 10.4 s, and 8.9 s; maximum overshoot values were 8.9 mm, 6.9 mm, 0.41 mm, and 0.62 mm; maximum undershoot values were 4.3 mm, 1.9 mm, 0.04 mm, and 0.2 mm, respectively. The results of the study were illustrated using graphs and tables and were further analyzed based on data thus obtained. Based on these analysis results, suggestions were made regarding the type of PLC that would be appropriate to be chosen for the system.

Keywords: PID, PLC, microcontroller, hydraulic propotional valve.

Hidrolik Oransal Valf Sisteminde Farklı PLC Serilerinin PID Kontrol Performanslarının Karşılaştırılması-Deneysel Bir Kurulum

ÖZ

Maliyetler ve üretim hızı endüstride çok önem kazanmıştır. Endüstriyel tesislerin kurulumu sırasında ideal özelliklere sahip malzeme seçimi, gerekli sistem performansının sağlanması açısından büyük önem arz etmektedir. Özellikle hareketli ekipmanlarla çalışırken sistemin gerektirdiği hızın yanı sıra gerekli ekipmanların maliyetleri de dikkate alınmaktadır. Bu çalışma, Kardemir AŞ. Ray ve Profil Haddehanesinde bulunan hidrolik oransal valf kontrolü sistemi için Siemens firmasına ait dört farklı CPU'ya sahip S7-300, S7-400, S7-1200 ve S7-1500 serisi PLC'lerin P, PI, PD ve PID kontrol modlarındaki performansları karşılaştırmaktadır. Performans karşılaştırmaları yerleşme süresi, yükselme süresi, gecikme süresi ve pozitif ve negatif maksimum aşımlar temel alınarak yapılmıştır. S7-300, S7-400, S7-1200 ve S7-1500 serisi PLC'ler için sırasıyla minumum oturma zamanı değerleri 18,4 s, 19,2 s, 10,4 s ve 8.9 s; maksimum üst aşım değerleri 8,9 mm, 6,9 mm, 0,41 mm ve 0,62 mm; maksimum altaşım değerleri 4,3 mm, 1,9 mm, 0,04 mm ve 0,2 mm olmuştur. Çalışmanın sonuçları grafikler ve tablolar kullanılarak gösterilmiştir ve elde edilen verilere dayanarak daha ayrıntılı olarak analiz edilmiştir. Bu analiz sonuçlarına göre sistem için seçilmesi uygun olan PLC tipine ilişkin önerilerde bulunulmuştur.

Anahtar Kelimeler: PID, PLC, mikrokontrolör, hidrolik oransal vana.

1. INTRODUCTION

Programmable Logic Controller (PLC) can be defined as a microprocessor-based control device or user-configurable microcontroller [1,2]. It has been widely used for automation applications and process control [2,3] over the last 50 years. PLCs are widely used in logical, arithmetic, binary, sequential, timing and counting applications with ease of communication and data manipulation in industries [4]. In order to implement control algorithms, modern PLCs present various requirements for analog inputs and outputs. Recent innovations in PLC have made significant progress in production environments by increasing efficiency as well as productivity and have led to exceptional results.

Today, the increase in energy, material and labor costs has led the industrial sector to take a series of measures in terms of savings. Companies making investments tend to get maximum efficiency from the products they use in their designs. For example, in the past, the microcontroller in the top segment with features and

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qualities that exceeded the needs of the project would be chosen for a particular task. Nowadays, they tend to choose a microcontroller that is cheap and has normal quality, with the minimum features required to complete the task. Similar situation exists in the case of Kardemir Inc. For example, in a system with approximately one hundred I/Os, S7-400 model PLC was previously selected where S7-300 model could be used easily and was sufficient in terms of performance, whereas in another system with a similar number of I/Os, the S7-1500 model PLC was used with a similar approach instead of a more affordable S7-1200 model that could be used.

Moving equipment are indispensable elements of industrial systems. Therefore, they have many areas of use in industrial systems and these systems need a control algorithm, especially in stop-start movements. Although many different control algorithms have been designed with the developing technology, the PID control method still continues its strong existence. Its most important advantage as compared to other algorithms is that it provides effective results in a short time by entering a small number of parameters. Sampling time is one of the most critical parameters in PID control, and the cycle time of the microcontroller used must meet the requirements and be compatible with this sampling time.

Different studies have been conducted in the literature based on controlling a system with PLC. Some of these studies are as follows: Control of the asynchronous motor was carried out with a PLC and Profibus communication [5]. A PLC-based multi-channel measurement system was developed [6]. A control system for water pump was designed to aid in production facilities and using the experimental setup, the system was implemented in the laboratory [7]. Considering the hydroelectric power plant (HEPP) as a real power plant, the design, manufacturing and control of the HEPP prototype device was carried out with PLC [8]. Automation Systems were simultaneously monitored and controlled with SCADA-based PLC [9]. A study was conducted aiming to provide energy management, monitoring-reporting and energy saving using a PLC and SCADA system from a single center [10]. An electro-pneumatic press prototype was designed with four different PLCs, open-source controllers and operator panels with different industrial communication protocols [11]. The energy monitoring automation system was designed with PLC and SCADA [12]. PLC-based fuzzy logic control of a deep drawing press machine was conducted effectively [13]. Linear robot control was achieved with image processing-based PLC [14]. Using PLC, vision-based real-time control of a linear robot platform was achieved [15]. A PLC controlled dryer conveyor was designed [16]. Using image processing, the process of separating objects was carried out in real time on the PLC-controlled conveyor belt system based on their colors [17].+

There are various studies conducted on PI and/or PID control using PLC. Some of these are as follows: A study was performed to adjust PI controllers with a more flexible structure based on generalized prediction for process control applications with PLC [18]. An experimental PID tuning application was designed with shallow controllers, PLC and deep reinforcement learning on a real physical system [19]. An automatically tuned proportional-integral controller was implemented using MATLAB-PLC communication in order to control the speed of a switched reluctance motor [20]. An adaptable Fuzzy logic-based approach was proposed for PID control of steam turbines in solar energy applications using PLC [21]. PID controller was designed for the set point voltage control problem in Automatic voltage regulator (AVR) system using MATLAB and PLC [22]. An automatically adjusted PID controller application was designed for the flow loop pilot plant with PLC and artificial neural network [23]. A micro hydroelectric power plant (MHPP) prototype was designed, fabricated and automated effectively. Frequency and voltage control was carried out using PLC and ANN [24]. In the literature review, no study could be found on the performance comparison of PID control of different CPUs.

The article has been organized as follows: Information regarding hydraulic systems and equipment is provided in Chapter 2. The experimental setup are explained in Chapter 3. The results and discussions are given in Chapter 4. Conclusions and recommendations are presented in Chapter 5.

2. THE HYDRAULIC SYSTEM AND EQUIPMENTS

2.1. Pump

Hydraulic fluid is kept in a container called a tank. The circuit element that ensures flow of liquid from the tank to the system at the desired or set pressure and flow rate is called a pump. Pumps convert mechanical energy into hydraulic energy. Pumps get their rotational motion from the electric motor. Contrary to popular belief, pumps do not create pressure. Pressure occurs spontaneously when the fluid encounters an obstacle in the system. The pump used in the experiments is shown in Figure 1.

Figure 1. Pump and the electric motor powering the pump

Hydraulic valves are mechanical equipment used to regulate the flow rate or intensity and direction of the fluid in a hydraulic system. They are used to redirect pressurized fluid, completely shut down a fluid line and control the flow level to another specific area. Designed in a wide variety of types, these valves can be controlled automatically or manually either by mechanical, pneumatic, physical, electrical or hydraulic control. Hydraulic valves can be described as equipment that can withstand very high amounts of fluid pressure. Therefore, they are made up of iron, steel or other metals with sufficient strength to withstand continuous operation in systems requiring very high pressures.
There are valves that operate with various control methods, the most commonly used types in the industry are electrically controlled valves. The well-known ones are lock valve, on-off valve, proportional valve and servo valves, respectively. There are also different types of electrically controlled proportional and servo valves. The valve used in the experiments is controlled with ± 10V. The length of the slide inside the valve is 10 mm, and when the control signal of the valve comes between -10 V and 0 V, it opens the valve slide between 0 mm and 5 mm. For example, when a -5 V signal is sent, the slide position of the valve will be 2.5 mm. When the control signal comes between 0 and 10V, the valve will open the slide between 5 mm and 10 mm. If +8 V signal is received, the valve will pull the slide to 9 mm. The proportional valve used in the experiments is shown in Figure 2.

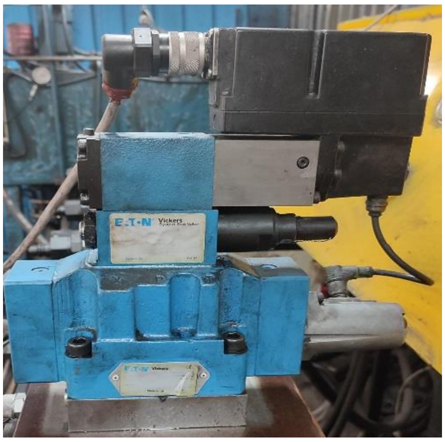

Figure 2. Hydraulic proportional valve

Technical specifications of the proportional valve are given in Table 1.

Table 1. Technical specifications of the proportional valve

Type	KBHDG5V-7 133C150N80N20 E X M1 PE7 H4 11
Flow Rating	160 L/min (42 USgpm)
Max Pressure, with pressure reducer	350 bar
Max Pressure, without pressure reducer	210 bar
Power Supply	24V DC
Command Signal	0 to 10V DC, or 0 to –10V DC, or –10V to + 10V DC
Input Impedance	M1: 47 kΩ - M2: 100R
Current Mode	4-20 mA

2.2. Cylinder

Hydraulic cylinders, also known as linear motors today, are equipment that convert the hydraulic energy of the fluid into mechanical energy. Almost all hydraulic systems ultimately drive a hydraulic cylinder. In general, they are mechanical equipment that move back and forth. Hydraulic cylinders are available in single-acting, double-acting, tandem and telescopic types and are used in a wide range of applications. All of the rollers used in the Rail and Profile Rolling Mill are double acting single shaft rollers, and this type of rollers is the subject of this study and used in the experiment.
In order for a hydraulic cylinder to provide the desired operation, it must be able to trap pressurized fluid without leaking. Internal or external leaks that may occur inside the cylinder may cause the pressure inside the cylinder to decrease and if it reaches a critical level, the cylinder cannot perform its desired function [3]. The hydraulic cylinder used in the experiments is shown in Figure 3.

Figure 3. Hydraulic cylinder

2.3. Linear Ruler

Linear rulers, also called linear potentiometers, can be referred to as a type of position sensors. Devices that detect the movement of an object and convert this movement into appropriate signals are known as position sensors. In addition, position sensors can also be used to measure the distance or displacement of an object. With these converted electrical signals, both the direction and intensity (amplitude) of the movement are measured. Therefore, in addition to linear scales, different devices such as linear encoders, potentiometers and rotary sensors can also be used. The most needed models in today's industry are linear scales and linear encoders. Linear rulers are especially preferred to measure linear movement.

Frequently, linear scales are also called non-contact linear encoders. The measurement principle is magneto strictive. Some models of these devices do not lose position information in case of a power outage. Thanks to these features, the position information of the shaft or cylinder to which it is connected is not lost when the electrical energy is restored.

The MTS/Tempo sonic brand linear ruler was used in the experiments. These sensors consist of a position magnet, a ferromagnetic waveguide, a voltage pulse converter and supporting electronic parts. In its use, the magnet attached to the moving object creates a magnetic field on the waveguide. This waveguide creates a torsional stress and instantaneous radial magnetic field when a very short pulse of current is applied to it. This momentary interaction of magnetic fields releases a torsional strain pulse that propagates down the length of the waveguide. The resulting ultrasonic wave is converted into an electrical signal when it reaches the end of the waveguide. Since the ultrasonic wave speed in the waveguide is already known, the time required to receive the return signal is converted into a linear position measurement with high repeatability and high accuracy. Since tempo sonic sensors provide absolute position information, they ensure that position information is transmitted without being lost in case of a power outage. Linear ruler used in the experiments is shown in Figure 4.

Figure 4. Linear ruler

3. EXPERIMENTAL SETUP

For the experiments, one hydraulic tank with a capacity of 200 liters, one hydraulic pump with a 37kW engine that can provide pressure between 280-350 bar, one hydraulic cylinder with a stroke length of 155 mm, one proportional valve operating in the range of ±10 V, one MTS brand sensor, linear ruler and four different Siemens brand PLCs were used. The materials used in the experiments are given in Table 2.

Table 2. Equipment used in the experiments

No	Equipment	Features
1	Hydraulic tank	200 lt
2	Hydraulic pump	280-350 bar, 37 kW motor
3	Hydraulic cylinder	155 mm stroke length
4	Proportional valve	Eaton brand, ±10 V analog output
5	Linear ruler	MTS sensor (GHM0150MD601A0, 4..20 mA)
6	PLC1	S7-314C-2 PN/DP, Siemens brand, S7-300 model, 196 KB work memory (order code: 314-6EH04-0AB0)
7	PLC2	S7-414-2 DP, Siemens brand, S7-400 model, 2 MB work memory (order code: 6SE7-414-2XG04-0AB0)
8	PLC3	S7-1214C, Siemens brand, S7-1200 model, 100 KB work memory (order code: 214-1AG40-0XB0)
9	PLC4	S7-1511C-1 PN, Siemens brand, S7-1500 model, 175 KB work memory (order code: 6ES7511-1CK01

Check valves, lock valves, directional valves, proportional and servo valves are used in the Rail and Profile Rolling Mill. Many of these valves fail as a result of the fluid mixing with the hydraulic fluid and passing through the filters, thus clogging these valves. A test unit was installed for faulty valves. The automation part of this test unit was prepared as seen in Figure 5.

Figure 5. Automation part of the experimental setup installed with S7-300 PLC

The test unit includes one power module, one S7-300 series PLC, one DI8xDC24V digital input card, one AI5/AO2x12Bit analog input-output card, one DO 32xDC 24V/0.5A digital output card, one AO 4x12Bit analog output card and a Simatic Touch Panel were used. Digital output modules were used for lock and directional valves, and analog output modules were used for proportional and servo valves, respectively. The position information of the cylinder was read by the analog input module.

Rail materials produced in Kardemir Inc. Rail and Profile Rolling Mill undergo geometric, superficial and ultrasonic tests in the test center. Physical controls of the chassis to which the probes used in these tests were connected were carried out by proportional valves driven by cards called DHVC. Feedback information was received by the linear ruler located on the hydraulic cylinders that enable the movement of the chassis and the metal proximity sensors that provide distance information to the rail. The program included in these DHVC cards was not given to Kardemir Inc. by the subcontractor company. In order to eliminate the malfunctions that occurred due to shortcomings of the program, monitor the operation of the system and intervene quickly in malfunctions, DHVC cards were canceled. Using the existing equipment and existing S7-400 series PLC, the FB41 PID control block present in the Siemens library was used to conduct PID control and redesign all probes connected to the chassis. The inquiry related to a suitable PLC alternative in the absence of an S7-400 series PLC within the current system for PID block implementation served as the starting point for this study because the S7-400 series PLC would be a very expensive solution for a system with a maximum of 200 I/O. Therefore, comparing the performances of the four different PLCs in the factory is the subject of this study.

For the S7-1200 and S7-1500 series, the PID_Compact block with pre-tuning and fine-tuning features was used. The values entered in the experiment related to the PID_Compact block are as follows: Setpoint variable, which is sent to the system as a set value of real type, was assigned to the Setpoint input. The scaled value taken from the linear scale, which is the feedback of the system, was entered into the input. The decimal value, which is the system output and sent to the valve, was entered in the Output_PER section.

The equation given for PID algorithm is as follows:

$$y = K_p \left[(b.w - x) + \frac{1}{T_I.s}(w - x) + \frac{T_D.s}{a.T_D.s + 1}(c.w - x) \right] \quad (1)$$

Where output value of the PID algorithm is denoted as y, proportional gain as K_p, proportional action weighting as b, Laplace operator as s, integral action time as T_I, set point as w, process value as x, derivative action time as T_D, derivative delay coefficient as a and derivative action weighting is denoted as c [25].

There is an IBA system in the Rail and Profile Rolling Mill, which instantly graphs the signals coming to the PLC, can record historical records and create online and offline trends accordingly. PLCs can also record data and get trends, but they cannot keep long records due to their memory restrictions. This is where systems such as IBA come into play. Both analog signals and digital signals can be recorded instantly in milliseconds. In addition to live viewing, retrospective recordings can also be viewed. The instantaneous value of the linear scale, which constitutes the main component of the system and gives the position information of the hydraulic cylinder and the set position value that should be reached were added to the existing IBA system to be examined.

PID block diagrams related to setpoint in the system is illustrated in Figure 6 below.

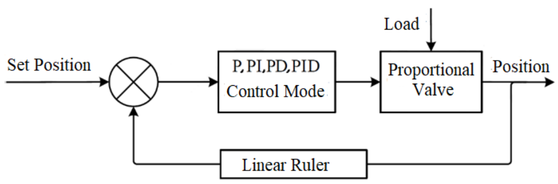

Figure 6. PID block diagram of the system

Program block of the S7-300 series PLC is given in Figure 7. The linear ruler was scaled in Network1 and the FB41 PID block was created in Network 2.

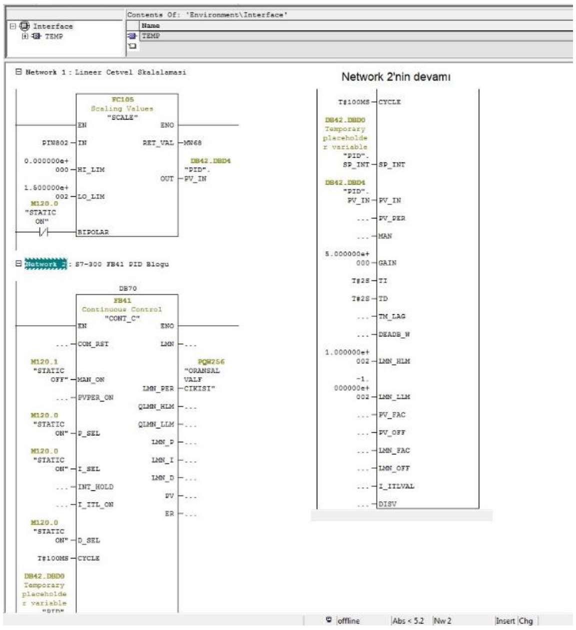

Figure 7. S7-300 PLC program block

Firstly, the proportional valve at the system was driven by the S7-300 series PLC, which was in the experimental set created for the test unit, with P, PD, PI and PID coefficients, respectively. S7-300 and S7-400 series PLCs do not have automatic calculation feature for PID parameters; therefore, these parameters are found as explained below. When PID control method needs to be used in any system or PID control circuit is created and there is no automatic control algorithm that calculates PID coefficients, the steps used for finding the appropriate coefficients are listed below.

- Firstly, the K_p value, which is the proportional layer coefficient, is adjusted. Meanwhile, the integral layer coefficient K_I and the derivative layer coefficient K_d are made zero. The coefficient is then gradually increased, starting from zero, in order to minimize the error in the output. This increase process continues until the permanent state error at the point where the real value K_P of the system is close to the set value, and the value stops increasing at the point where it is closest.

- Secondly, the K_D value, which is the derivative layer coefficient, is increased until the maximum exceedance decreases to an acceptable level, without changing the K_p coefficient value found in the first step and the K_i coefficient value set to zero. The oscillation of the real value around the set value of the system is checked and the K_d value adjustment process is stopped at the minimum amplitude oscillation.

- A steady-state error occurs at the system output with the K_p and K_d coefficient values found in the first and second steps. The value of K_i, which is the integral layer coefficient, is increased until this error reaches zero. If this error is not reset despite increasing the K_I coefficient, the adjustment process is stopped at the point closest to zero.

P (proportional) graph (K_p =1 K_i =0 K_d=0), P (proportional) graph, (K_p =5 K_i =0 K_d=0), PD (proportional-derivative) graph (K_p =5 K_i =0 K_d =1), PD (proportional-derivative) graph (K_p =5 K_i =0 K_d=10), PI (proportional-integral) graph, (K_p =5 K_i =1 K_d=0), PI (proportional-integral) graph (K_p =5 K_i =10 K_d=0) and PID (proportional-integral-derivative) graph (K_p =5 K_i =2 K_d=1) were obtained, respectively. Two of these seven graphs obtained are given as examples in Figures 8 and 9.

Integers were specifically used for K_p, K_i, and K_d because there is infinite variation when determining optimal parameters. The proportional coefficient was initiated from 1 and was tried up to 10, respectively. In trials between 1 and 5, the maximum overshoots decreased as it approached 5, and increased again as it approached 10 from 5, so the optimum value was chosen as 5. Similarly, derivative and integral coefficients were also found.

Manual parameter adjustment cannot provide theoretically perfect coefficients, but acceptable overshoot, undershoot and settling time can be found for the system. Geometric, surface, and ultrasonic tests are performed on the rails in the test center department of Rail and Profile rolling mill. The system is used to control the approach distances of the chassis carrying the sensors that perform measurements to the rail. It is very important for the settling time to be minimal and for the maximum undershoot and overshoot not to exceed 10% in order for the tests to be fast and safe. The system is used to monitor and control the distance between the moving rail and the measurement probes. At maximum deviations, the probes should neither contact the rail nor go beyond the measurement distance. The detection distance for the probes to perform measurements is 15 mm. For safe operation, the probes are allowed to approach the rail up to a maximum of 5 mm. In the actual system, when the set value is chosen as 10 mm, an overshoot and undershoot of 10% are acceptable error margins for measurement distance and safety. In the rail and profile rolling mill process, there is an average time interval of 180 seconds between the entries of the two rails into the test center. To allow operators to intervene in case of a possible malfunction, the settling time is optimally decided to 30 seconds. Based on these data, acceptable maximum overshoot, undershoot and settling time values for these experiments determined as 10% (10 mm), 10% (10 mm) and 30s, respectively. Manual PID parameter adjustment processes were continued until it fell below these acceptable values.

In the graphs, time (in hours, minutes and seconds) is shown in the horizontal axis and position value (in mm) is shown in vertical axis. The signal shown in red on the vertical axis shows the set position value and the signal shown in blue shows the feedback value received from the linear ruler. The graphics show the image of the IBA Analyzer program, where historical records can be viewed.

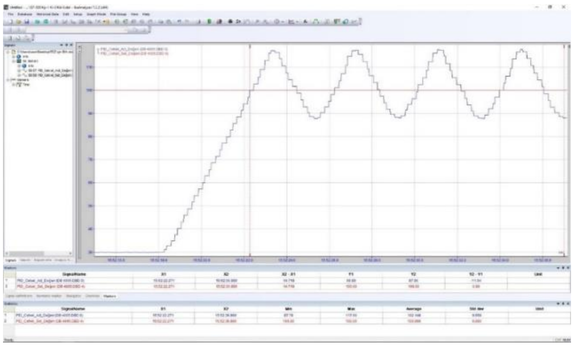

Figure 8. S7-300 P (proportional) graph (K_p =1, K_i =0, K_d=0)

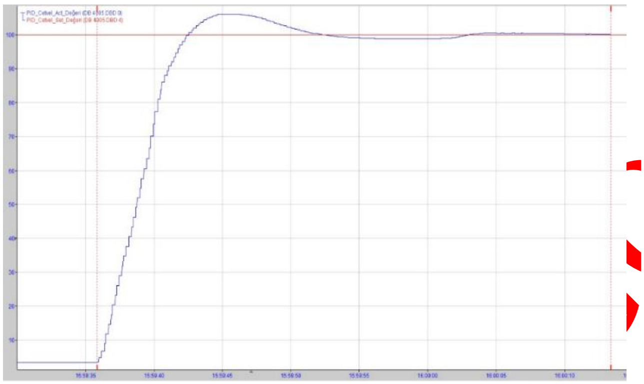

Figure 9. S7-300 PID (proportional-integral-derivative) graph (K_p=5, K_i =2, K_d=1)

The program block of the S7-400 series PLC is given in Figure 10. The linear scale was scaled in Network-9 and the FB41 PID block was created in Network-10.

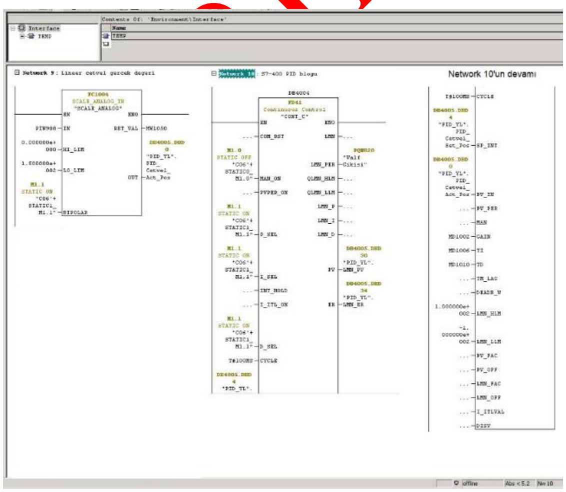

Figure 10. S7-400 PLC program block

The S7-400 series PLC used in the Rail and Profile rolling mill was driven with the same P, I and D coefficients used in the S7-300 series. Two of the seven graphs obtained as examples are given in Figures 11 and 12 respectively.

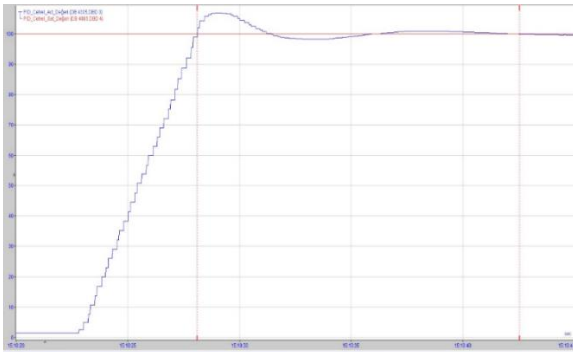

Figure 11. S7-400 PI (proportional-integral) graph (K_p=5, K_i =1, K_D=0)

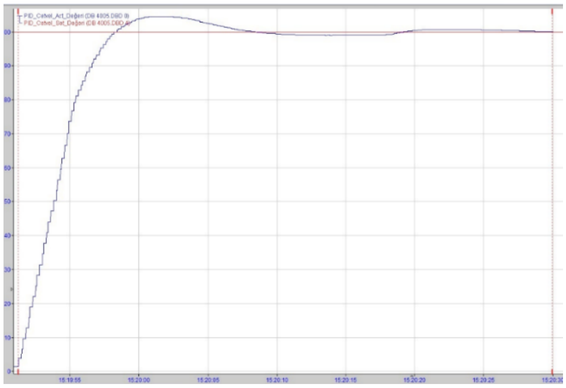

Figure 12. S7-400 PID (proportional-integral-derivative) graph (K_p=5, K_i =2 K_D=1)

The program block of the S7-1200 series PLC is given in Figure 13. The linear ruler was scaled in Network 1 and the PID_Compact block was created in Network 2.

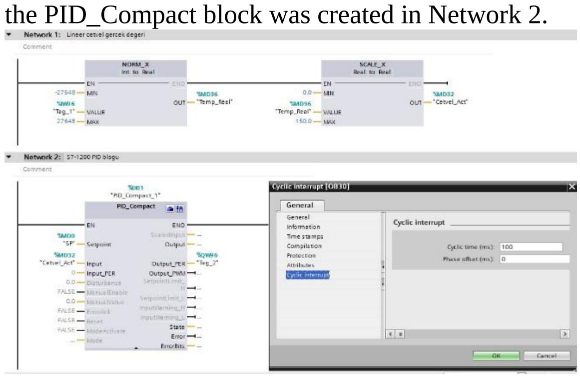

Figure 13. S7-1200 PLC program block

Thirdly, the proportional valve at the system outlet was driven in the TIA portal interface with the S7-1200 PLC. In the TIA portal environment, pre-tuning and fine-tuning features that automatically adjust PI and PID parameters are available. PI fine-tuning result is shown in Figure. 14 and its parameters are given in Figure 15.

PID fine-tuning result has been shown in Figure 16 and its parameters are shown in Figure 17.

In the graphs given in Figure 14 and Figure 16, time (in hours, minutes and seconds) is shown in the horizontal axis and position value (in mm) is shown in vertical axis. The signal shown in red on the vertical axis shows the set position value and the signal shown in blue demonstrates the feedback value received from the linear ruler.

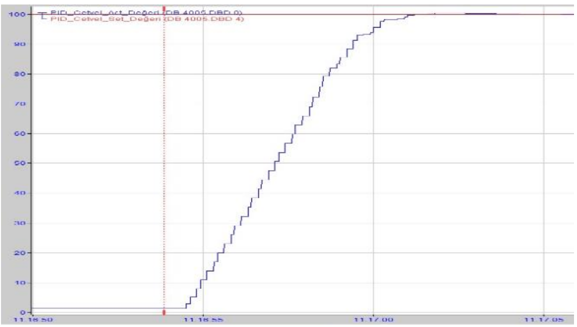

Figure 14. S7-1200 PI graph (Fine-Tuning)

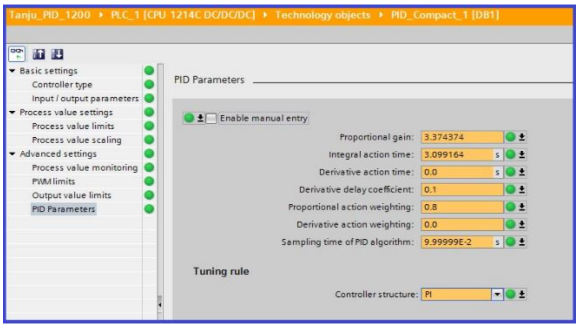

Figure 15. S7-1200 PI parameters (Fine-Tuning)

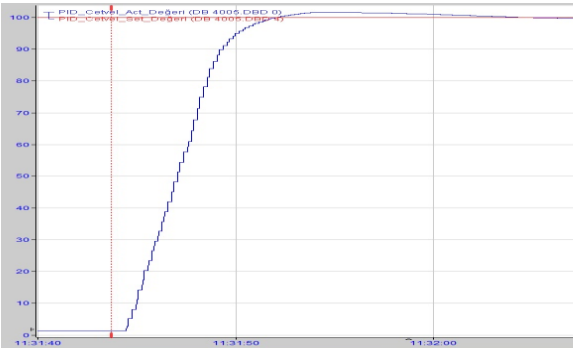

Figure 16. S7-1200 PID graph (Fine-Tuning)

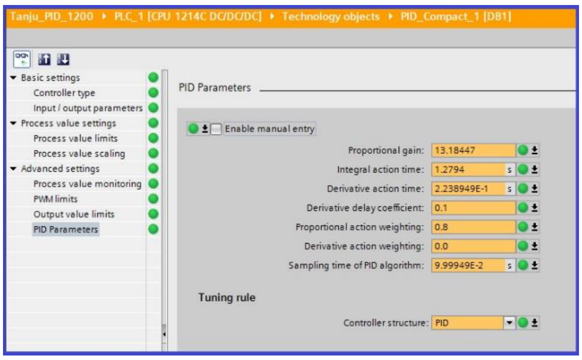

Figure 17. S7-1200 PID parameters (Fine-Tuning)

The program block of the S7-1500 PLC is given in Figure 18. The linear ruler was scaled in Network 1 and the PID_Compact block was created in Network 2.

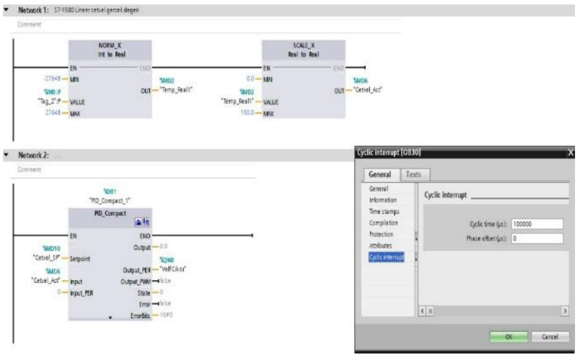

Figure 18. S7-1500 PLC program block

Finally, the proportional valve at the system outlet was driven by the S7-1500 series PLC in the TIA portal interface. PI fine-tuning result is shown in Figure 19 and its parameters are shown in Figure 20. The PID fine-tuning result is shown in Figure 21 and its parameters are shown in Figure 22.

In the graphs given in Figure 19 and Figure 21, time (in hours, minutes and seconds) is shown in the horizontal axis and position value (in mm) is shown in vertical axis. The signal shown in red on the vertical axis shows the set position value and the signal shown in blue shows the feedback value received from the linear ruler.

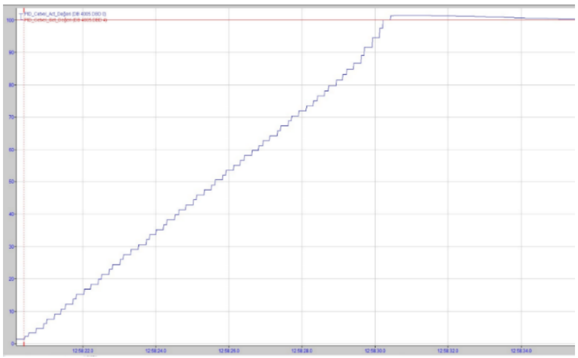

Figure 19. S7-1500 PI graph (Fine-Tuning)

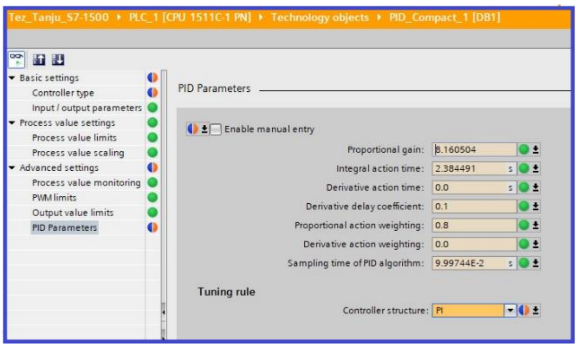

Figure 20. S7-1500 PI parameters (Fine-Tuning)

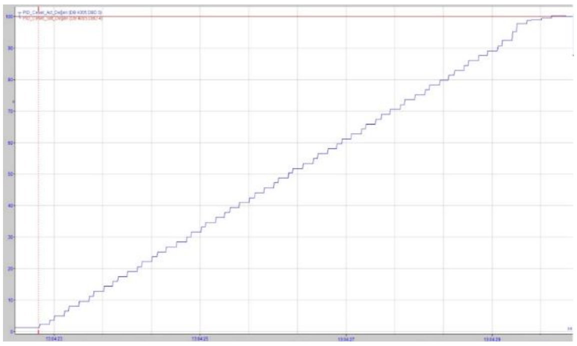

Figure 21. S7-1500 PID graph (Fine-Tuning)

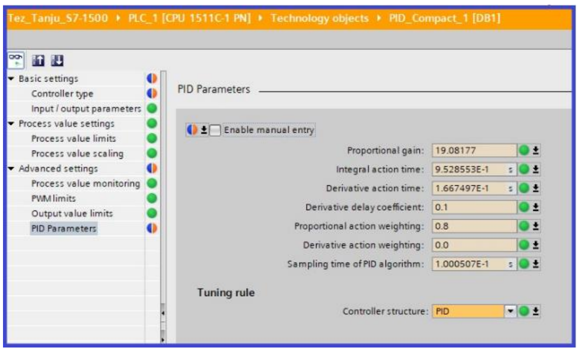

Figure 22. S7-1500 PID parameters (Fine-Tuning)

4. RESULTS AND DISCUSSIONS

In the experimental setup, four different control methods (P, PD, PI, PID) were used with S7-300 and S7-400 series PLCs, and two different (PI and PID) were used with S7-1200 and S7-1500 series PLCs. The results obtained were interpreted as follows.

The result table obtained with the PID parameters of the S7-300 PLC is given in Table 3, and the result table obtained with the PID parameters of the S7-400 series PLC is given in Table 4. In the first line of Table 3 and Table 4, the instantaneous values at which the control started and taken from the linear ruler were recorded. In the second line, the set position, which is common to all and is the position where the cylinder is desired to go, were entered. In order to find the rise time, 10% and 90% values of the total distance were entered in the third and fourth lines, and the time between these values was entered as the rise time in the fifth line. Similarly, in order to find the delay time, the starting position (0% position value) and 50% position values were entered in the sixth and seventh lines, and the remaining time was entered as the delay time in the eighth line. In the ninth and tenth lines, the maximum overshooting and maximum undershooting values above and below the set value encountered when reaching the set value were entered. Finally, in the eleventh line, the settling time value of the controller was entered.

Proportional (P) control was examined by entering proportional control values with the coefficient K_p=1 in the first column and with the coefficient K_p=5 in the second column of Table 3 and Table 4, respectively. Similarly, PD control was examined by entering K_p=5, K_d=1 and Kp=5, K_D=10 in the third and fourth columns. Likewise, proportional-integral control (PI) was examined by entering K_p=5, K_i=1 and K_p=5, K_i=10 in the fifth and sixth columns, respectively. In the last column where S7-300 and S7-400 series PLCs are examined, K_p=5, K_i=2, K_d=1 coefficients and PID control values were entered.

S7-1200 and S7-1500 series PLCs have a Fine-Tuning feature. This feature was created by Siemens only for S7-1200 and S7-1500 series PLCs. Therefore, PID coefficients were entered manually since they are not available in the S7-300 and S7-400 series.

Table 3. S7-300 PLC PID control

S7-314C-2 PN/DP PLC	P		PD		PI		PID
	K_p=1	K_p=5	K_p=5, K_d=1	K_p=5, K_d=10	K_p=5, K_i=1	K_p=5, K_i=10	K_p=5, K_i=2, K_d=1
Initial Position (mm)	29.9	4.19	4.12	1.45	3.91	4.01	3.32
Set Position (mm)	100	100	100	100	100	100	100
10% Position Value (mm)	36.91	13.771	13.708	11.305	13.519	13.609	12.988
90% Position Value (mm)	92.99	90.419	90.412	90.145	90.391	90.401	90.332
Rising Time (10%-90%) (s)	3.2	4.5	4.38	4.38	4.31	7.8	4.29
0% Position Value (mm)	29.9	4.19	4.12	1.45	3.91	4.01	3.32
50% Position Value (mm)	64.95	52.095	52.06	50.725	51.955	52.005	51.66
Delay Time (0%-50%) (s)	2.12	2.83	3.01	2.82	3	2.9	2.93

Maximum Overshoot (mm)	17.6	10.6	10.8	8	8.9	0.11	6.1
Maximum Undershoot (mm)	12.3	8.1	7.2	4.6	4.3	0.11	1.1
Settling Time (s)	Between 87-117 oscillation	Between 91-110 oscillation	Between 92-110 oscillation	Between 95-108 oscillation	18.38	47.5	37.5

For S7-300 PLC, when K_p=5 in P control mode, the maximum overshoot decreased as compared to K_p=1, but the rise time and delay time were observed to be increased. However, it was observed that it oscillated at both values and even at higher values. After P control, PD (Proportional-Derivative) control was tested, however, oscillations were observed in the system output here too. Then, PI (Proportional-Integral) experiments were carried out, and in these experiments, the K_p coefficient was kept constant at 5 and the Ki value was tested with the values 1 and 10, respectively. Although the maximum overshoot amount decreased when the Ki value was 10 compared to the value 1, the settling time increased significantly. After all these results, the PID experiment was tried with the values K_p = 5, K_i = 2, K_d = 1. According to these values, the system settled and became stable in 37.5 seconds with acceptable overshoot values.

Table 4. S7-400 PLC PID control

S7-414-2 DP PLC	**P**		**PD**		**PI**		**PID**
	K_p=1	K_p=5	K_p=5, K_D=1	K_p=5, K_p=10	K_p=5, K_i=1	K_p=5, K_i=10	K_p=5, K_i=2, K_D=1
Initial Position (mm)	150	150	150	1.41	1.42	1.41	1.41
Set Position (mm)	100	100	100	100	100	100	100
10% Position Value (mm)	145	145	145	11.269	11.27	11.269	11.269
90% Position Value (mm)	105	105	105	90.141	90.14	90.141	90.141
Rising Time (10%-90%) (s)	2.28	2.31	2.33	4.56	4.13	7.4	4.76
0% Position Value (mm)	150	150	150	1.41	1.42	1.41	1.41
50% Position Value (mm)	125	125	125	50.705	50.71	50.705	50.705
Delay Time (0%-50%) (s)	1.5	1.41	1.54	2.81	2.64	2.6	2.66
Maximum Overshoot (mm)	17.1	10.8	9.8	8.1	6.9	2.7	4.5
Maximum Undershoot (mm)	11.9	7.4	7.5	3.8	1.9	2.8	1
Settling Time (s)	Between 87-117 oscillation	Between 92-110 oscillation	Between 92-110 oscillation	Between 96-108 oscillation	19.21	31.52	37.9

S7-400 series PLC has been tested with the same parameters used in S7-300 series PLC. According to K_p=1 in P control, the rise time of the S7-400 series PLC was found to be 29% better. This resulted in a 32% improvement in delay time. Although the system showed oscillations in both PLCs, the maximum overshoots in the S7-400 series were less as compared to the S7-300 series PLC. According to K_p=5, the rise time was found to be 48.6% better. This resulted in a 50% improvement in delay time. Although the system showed oscillations in both PLCs, the maximum overshoots in the S7-400 series were detected to be slightly lower than the S7-300. In PD control, the rise time of the S7-400 series PLC was found to be 46% better as compared to K_p = 5 and KD = 1. This resulted in a 48.8% improvement in delay time. Although the system showed oscillations in both PLCs, the maximum overshoots in the S7-400 series were slightly lower than the S7-300. Compared to K_p=5, K_d=10, the rise time of the S7-400 series PLC was 4% worse. Delay times were similar with a negligible difference. In both PLCs, the system showed oscillations at the same levels. Maximum and minimum overshoots were almost the same.

In PI control, the rise time of the S7-400 series PLC was 4% better as compared to $K_p = 5$, $K_i = 1$. It was 2.4% better in delay time. For the settling time, the S7-300 series PLC was 4.5% better than the S7-400. Additionally, maximum overshoots were found to be less in the S7-400 PLC. Compared to K_p=5, K_i=10, the rise time of the S7-400 series PLC was 5% better. This resulted in a 10% improvement in delay time. For the settling time, the S7-400 series PLC showed 33.6% better performance than the S7-300. However, the maximum overshoots were found to be less in the S7-300 PLC, albeit with small differences.

Finally, according to the coefficients K_p=5, K_i=2, K_d=1 in PID control, the rise time of the S7-300 series PLC was observed to be 10% better. In this case, the S7-400 series PLC was 9% better in delay time. As for settling time, S7-300 series PLC performed better with a very small difference. It was also observed that the maximum overshoots were very close to each other.

The result table of the S7-1200 series PLC in PID control mode is given in Table 5, and the result table in the PID control mode of the S7-1500 series PLC is given in Table 6. In the first line of Tables 5 and 6, the instantaneous values at which the control started and taken from the linear scale were recorded. In the second line, the set position, which is common in all and is the position where the cylinder is desired to go, was entered. In order to find the rise time, 10% and 90% values of the total distance were entered in the third and fourth lines, and the time between these values was entered as the rise time in the fifth line. Similarly, in order to find the delay time, the starting position (0% position value) and 50% position values were entered in the sixth and seventh lines, and the remaining time was entered as the delay time in the eighth line. In the ninth and tenth lines, the maximum overshoot and maximum undershoot values above and below the set value encountered when reaching the set value were entered. Finally, in the eleventh line, the settling time value of the controller was entered.

Table 5. S7-1200 PLC PID control

S7-1214-C PLC	**PI**	**PID**
Initial Position (mm)	1.41	1.43
Set Position (mm)	100	100
10% Position Value (mm)	11.269	11.287
90% Position Value (mm)	90.141	90.143
Rising Time (s) (10%-90%)	4.47	4.3
0% Position Value (mm)	1.41	1.43
50% Position Value (mm)	50.705	50.715
Delay Time (s) (0%-50%)	4.92	2.7
Maximum Overshoot (mm)	0.41	1.52
Maximum Undershoot (mm)	0.04	0.069
Settling Time (s)	10.4	19.7

Table 6. S7-1500 PLC PID control

S7-1511C-1 PN PLC	**PI**	**PID**
Initial Position (mm)	1.39	1.39
Set Position (mm)	100	100
10% Position Value (mm)	11.25	11.25

90% Position Value (mm)	90.13	90.13
Rising Time (s) (10%-90%)	8.2	7.3
0% Position Value (mm)	1.39	1.39
50% Position Value (mm)	50.69	50.69
Delay Time (s) (0%-50%)	5.3	4.7
Maximum Overshoot (mm)	1.4	0.62
Maximum Undershoot (mm)	0.8	0.2
Settling Time (s)	15.2	8.9

The interface and PID program blocks of S7-300 and S7-400 series PLCs and the interface and PID program blocks of S7-1200 and S7-1500 series PLCs are different from each other. In order to see the effect of these differences on PID outputs in the experiment, the parameters entered in the FB41 block in the Simatic Manager program were entered in the PID_Compact block in the TIA portal program. However, using S7-1200 and S7-1500 series PLCs with same parameters, the system could not reach the entered set value in any case and showed oscillations.

According to the Fine-Tuning parameters of both PLCs for PI control, the rise time of the S7-1200 series PLC was 45% better and the delay time was 7% better. In terms of settling time, the S7-1200 series PLC was 31% better. In addition, in the overshoot comparison, it was seen that the performance of both PLCs was very good and there was a negligible difference between them. According to the Fine-Tuning parameters of both PLCs for PID control, the rise time was 41% better in S7-1200 series PLC, similar to the result in the PI control. In terms of delay time, the S7-1500 series PLC was 42% better. In the settling time comparison, S7-1500 series PLC was 54% better which is completely opposite to the PI control result. In addition, in the overshoot comparison, it was seen that the performance of both PLCs was very good and there was a negligible difference between them.The best performance values of four different series PLCs are given in Table 7. Since it is crucial for this system that the maximum overshoot and undershoot values do not exceed 10% (10 mm) and that the settling time is minimized, the values obtained when the overshoots do not exceed 10% and the settling time is minimized are considered to be the best values.

Table 7. The best control results of all PLCs

PLC and Control Mode	**S7-300**	**S7-400**	**S7-1200**	**S7-1500**
	PI (K_p=5, K_i=1)	**PI** (K_p=5, K_i=1)	**PI**	**PID**
Initial Position (mm)	3.91	1.42	1.41	1.39
Set Position (mm)	100	100	100	100
10% Position Value (mm)	13.51	11.27	11.269	11.25
90% Position Value (mm)	90.39	90.14	90.141	90.13
Rising Time (s) (10%-90%)	4.31	4.13	4.47	7.3
0% Position Value (mm)	3.91	1.42	1.41	1.39
50% Position Value (mm)	51.96	50.71	50.705	50.69
Delay Time (s) (0%-50%)	3	2.64	4.92	4.7
Maximum Overshoot (mm)	8.9	6.9	0.41	0.62
Maximum Undershoot (mm)	4.3	1.9	0.04	0.2
Settling Time (s)	18.4	19.2	10.4	8.9

6. CONCLUSIONS AND SUGGESTIONS

The FB41 block used in the Simatic Manager program and the PID_Compact blocks used in the TIA portal program work on different platforms as software. There is an "Anti-Windup" block in the algorithm of the PID_Compact block, but this block is not available in the FB41. Therefore, when comparing these four PLCs, it would be more suitable to compare S7-300 series PLC and S7-400 series PLC, and S7-1200 series PLC and S7-1500 series PLCs among themselves.

In order to accurately compare S7-300 series PLC and S7-400 PLC, the sampling times were entered as 100 ms. According to the test results, it has been concluded that in applications where low overshoots are important and short settling times are required, using S7-400 series PLC instead of S7-300 series PLC will be more suitable for the desired performance. However, in applications where settling times are not critical (for example, temperature control applications), S7-300 series PLCs will be more cost-effective.

It can be seen from the experimental results that the Pre-Tuning and Fine-Tuning features in the S7-1200 and S7-1500 series PLCs, which are the new generation PLCs as compared to the S7-300 and S7-400 PLCs, provide better results than manual parameter adjustment. Considering the rise time, settling time and overshoots specifically for S7-1200 and S7-1500, it is observed that PI control gives better results for the S7-1200 series PLC and PID control gives better results for the S7-1500 series PLC in the system established for the study. Among all PLCs, the best result in terms of settling time was obtained in the S7-1500 series PLC. However, since there are not much differences between them and the S7-1200 series PLC, the choice is determined by cost and signal intensity. It has been concluded that it would be more cost-effective to use S7-1500 when a system with a high processing load is installed and S7-1200 in systems where the processing load is normal.

In future studies, more experiments are planned to be conducted on different systems and the PID control performances of these PLCs will be evaluated in more detail.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Tanju KOCAKAYA: Conceptualization, Methodology, Software, Writing.

Hüseyin ALTINKAYA: Conceptualization, Methodology, Reviewing, Editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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