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Development of a Rolling Stock Door Control Unit (DCU) using Outseal Programmable Logic Controller (PLC)

Sulfan Bagus Setyawan
Dept of Computer Control Engineering
Politeknik Negeri Madiun,
Madiun, Indonesia
sulfan@pnm.ac.id

Muhammad Rifqi Agung
Dept of Rolling Stock Engineering
Politeknik Negeri Madiun
Madiun, Indonesia

Wahyu Pribadi
Dept of Rolling Stock Engineering
Politeknik Negeri Madiun
Madiun, Indonesia

R. Akbar Nur
Dept of Rolling Stock Engineering
Politeknik Negeri Madiun
Madiun, Indonesia

Wida Yuliar Rezika
Dept of Rolling Stock Engineering
Politeknik Negeri Madiun
Madiun, Indonesia

Abstract:- Currently, the train door settings lack a speed control system with closed-loop control, relying on manual tuning to ensure uniform door speeds. To address this limitation, this research focuses on developing a Door Control Unit (DCU) to regulate the train doors' condition and manage the opening and closing speed.The DCU system relies on a Programmable Logic Controller (PLC) as its foundation, enabling seamless communication with other PLCs through the RS485 communication line using the Modbus RTU protocol in a master-slave configuration. Consequently, this setup facilitates integration with various control devices, enhancing the overall efficiency of the train door operation. The DCU employs a Proportional-Integral-Derivative (PID) control method with a closed-loop system, coupled with PWM Duty Cycle output adjustments. By applying the Ziegler-Nichol's type 1 PID control method, the obtained control parameters are Kp = 2.4, Ki = 12, and Kd = 0.12. Experimental tests reveal certain characteristics of the system, such as delay time (0.2s), rise time (0.1s), steady time (0.8s), overshoot (%mp) at 28.75%, and steady-state error at 1.

Keywords:- *Door Control Unit (DCU), Programmable Logic Controller (PLC), PID, Ziegler-Nichol's, Modbus RTU.*

I. INTRODUCTION

Indonesia, being densely populated, experiences increased activity and mobility within its borders. As a result, the country heavily relies on mass transportation to facilitate daily human endeavors. Among the various mass transportation options, trains play a crucial role, operating on railroads or designated lines. These rail systems serve as effective means of transportation within cities, between cities, and even between countries [1]

According to the statement by the Minister of Transportation of the Republic of Indonesia, the Jabodetabek Electric Rail Train (KRL) - serving Jakarta, Bogor, Depok, Tangerang, and Bekasi - carries a staggering 1.2 million passengers daily [2]. The Ministry of Transportation's Regulation (PM) number 54 of 2016 defines railway facilities, including locomotives, trains, carriages, and specialized equipment [3].

Train classification, based on Stadler Rail AG's train manufacturing industry, includes fast trains, inter-city trains, inter-provincial trains, and inner-city trains. Among the critical components of a train, the train door holds significant importance. Serving as the point of entry and exit for passengers, it is the most frequently used part of the train, directly impacting passenger practicality, comfort, reliability, and safety [4]. Typically, trains incorporate three types of doors: Swing Doors, Sliding Doors, and Slide and Plug Doors, each operated manually, pneumatically, or electrically. Ensuring efficient functioing of these doors is crucial for enhancing the overall train experience for passengers.

The train door serves as a vital exterior component and plays a crucial role in the train's security system. Discussions with PT INKA and reference to existing technical specifications reveal that the train door control is a primary safety system. If the train door is not fully closed, the train cannot be operated by the driver. Additionally, the train door is designed not to open while the train is running at a specific speed. A concrete incident supporting this importance occurred with the Palembang LRT (Light Rail Transit) train in 2018. The train came to a halt in the middle of the crossing due to a door sensor failure, triggering the train's failure-safe system [5]. Typically, the train door system's controller communicates with the main controller known as the Train Control Management System (TCMS). Commonly employed communication protocols include Modbus RTU, Modbus TCP, and CAN protocols. Data from the train door system's controller is transmitted to the Human Machine Interface (HMI) situated in the driver's cabin. According to PT INKA interviews, certain train doors do not utilize a closed-loop controller for each door, leading to time discrepancies between different doors during opening and closing operations.

Drawing from existing research and identified issues, the researcher intends to conduct a study on a Rolling Stock Door Control Unit (DCU) using Programmable Logic Controller (PLC) technology. The aim is to devise a solution for Sliding Door Electric trains that can operate in a closed-loop system, enabling precise adjustments of the door's opening and closing speeds. By implementing the Proportional, Derivative, and Integral (PID) methods, known for their stable control capabilities, the research seeks to enhance the door speed settings, aligning them with the safety requirements of the railroad industry to ensure the well-being of users.

II. RELATED WORKS

Below are several previous research used as references, research by Joung [7] development of electric plug door and test results explains the operation of the Door Control Unit (DCU), which receives data from Door Closing Switch (DCS), Door Locking Switch (DLS), Emergency Lever, and Individual Door Open Switch. In this research, the communication protocol between DCU and Train Control & Management System (TCMS) utilizes RS485 cable, while RS232C is used as a pathway for downloading self-diagnostic data from DCU and uploading necessary firmware to DCU.

Rattanachan, Nuchkum, and Leeton [8] conducted research about Electric Door Control System using MRS Developers Studio for Low-floor Bus to control the opening, closing, and obstacle avoidance of Sliding Door Electric using MRS Developer Studio CAN IO Module. The Door Control principle employed is based on PWM control to regulate the motor's speed during the door opening and closing processes. The process of opening the door starts with a PWM Duty Cycle initially set at 50% and gradually decreasing to 30% and then 20% until the door is fully closed. This process takes approximately 3 seconds. During the closing process, the PWM Duty Cycle is set at 20% from the beginning until closing, resulting in the closing process taking less than 6 seconds. During the testing process of obstacle avoidance when closing, a time-based system is utilized. If the closing process exceeds 6 seconds, the motor will revert, reopening the door until it is fully open

In another research by Adam [9] about design and Implementation of Outseal PLC for Controlling DC Motor with Various Speed Variations), it was found that PLC Outseal can regulate motor speed using the Pulse Width Modulation (PWM) method. The addition of components such as the Buck Converter is necessary because the PWM output on the R7 pin of PLC Outseal, which comes from the duty cycle value, is insufficient to drive the 180 VDC motor. The study demonstrated that PLC Outseal is capable of controlling the DC motor speed, with higher duty cycle values resulting in faster motor rotations.

Changying et al. (2015) conducted a study titled "Control Method of High-Speed Train Automatic Side Door Based on Gravitational Search Algorithm" to control the Sliding Door Electric with a PID control system on a 24V, 4.5A current ratio, 94.7 W power, 3350 rpm set point rotation, 105mm transmission gear diameter, and 50kg door weight DC motor. The study aimed to achieve the appropriate steady-state motor value, which took approximately 0.4 seconds.

The block diagram shown in Figure 1 can be elucidated as follows. The primary role of the Programmable Logic Controller (PLC) on the DCU panel is to act as the main controller, receiving commands from either the PLC Master or the Human Machine Interface through the Modbus RTU RS485 protocol. Additionally, the PLC on the DCU panel

III. PROPOSED METHODS

A. Proposed System

The block diagram shown in Figure 1 can be elucidated as follows. The primary role of the Programmable Logic Controller (PLC) on the DCU panel is to act as the main controller, receiving commands from either the PLC Master or the Human Machine Interface through the Modbus RTU RS485 protocol. Additionally, the PLC on the DCU panel functions as a control system responsible for regulating the motor's rotation speed through the motor driver and reading the door sensors. The PWM to Voltage device serves to convert the duty cycle value from the PLC into a voltage within the range of 0 to 10 VDC. Meanwhile, the Motor Driver acts as the controller for the Brushless Direct Current Motor (BLDC Motor).

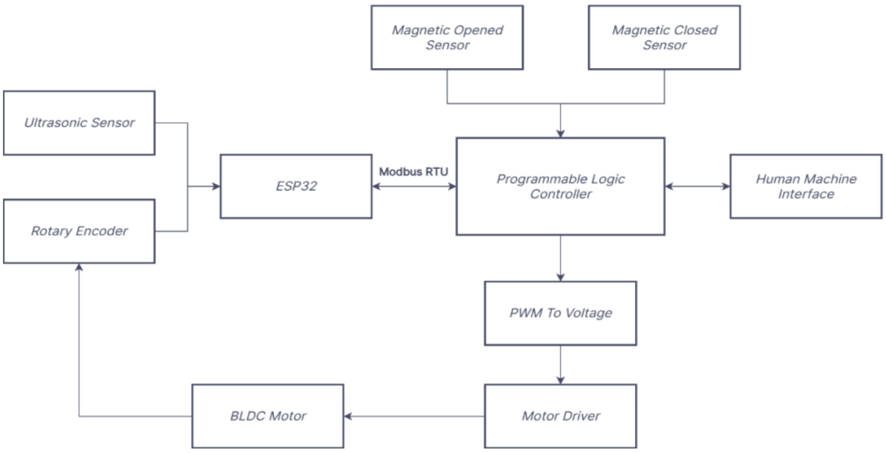

Fig. 1. Block Diagram System

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Fig. 2. Dcu controller

The Brushless Direct Current Motor (BLDC Motor) operates as the actuator responsible for moving the door, rotating either clockwise or counterclockwise. The Magnetic Opened/Closed Sensor is utilized to detect the door's condition, whether it is opened or closed, through a magnet placed on the door. This sensor is positioned directly on the door frame. Additionally, a rotary encoder is mounted on the BLDC motor to track the number of rotations made by the BLDC motor during the door's opening or closing process.

The Ultrasonic Sensor serves the purpose of detecting objects on the doors using ultrasonic waves, helping to identify any obstructions when the door is closing. The ESP32 acts as a controller for reading values from the ultrasonic sensor and the number of pulses from the Rotary Encoder. The collected data is processed on the ESP32 and then transmitted to the PLC via Modbus RTU communication

Lastly, during testing, the Human Machine Interface (HMI) plays a crucial role. It is used to test issuing commands and reading DCU conditions using the Modbus RTU RS485 communication protocol.

B. Door Control Unit electrical design

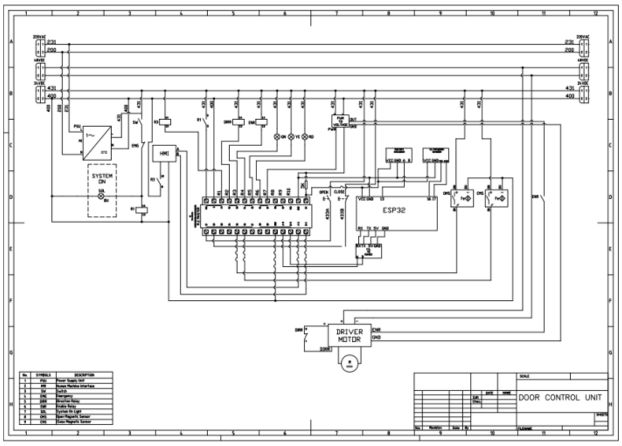

Fig. 3. Door Control Unit electrical design

The electrical design phase of the Door Control Unit involves creating Wiring Diagram documentation using the Autocad Electrical application. This design process entails selecting appropriate components from available products in the market and representing them in drawings. These drawings serve to streamline the assembly process of the Door Control Unit panel, making it more straightforward and efficient.

C. Programmable Logic Controller (PLC)

A Programmable Logic Controller (PLC) is an advanced electronic circuit capable of executing a wide range of complex control tasks. PLCs can be easily programmed, controlled, and operated by individuals who may not have extensive experience with computers. Typically represented with lines and equipment on diagrams, one of the common programming languages for PLCs is the Ladder Diagram. Additionally, PLCs can be programmed using various other languages such as Structured Text, Continuous Function Charts, Sequential Function Charts, and Function Block Diagrams

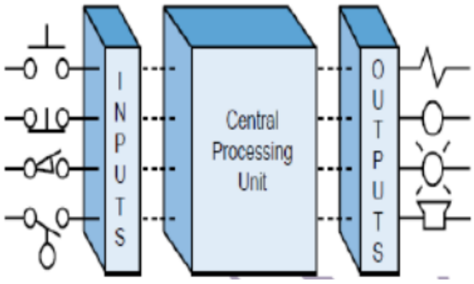

Fig. 4. PLC system

PLC construction as shown in Figure 3 consists of Input Unit, Central Processing Unit, Memory Unit, and Output Unit. The Input Unit section is responsible for receiving data that will be sent by analog signals or digital signals depending on the Analog to Digital Converter (ADC) or Digital to Analog Converter (DAC) converter. The Central Processing Unit is responsible for storing data in memory on the PLC. The Memory Unit is responsible for storing all types of data such as programs and instructions. The output functions as a digital signal sender to relays, contactors, lamps, and also sends analog signals in the form of DC currents or voltages (Khudier, Mohammed and Ibrahim, 2021).

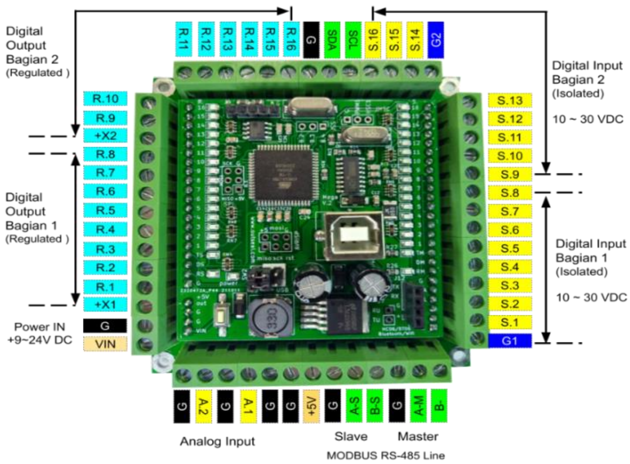

Fig. 5. OUTSEAL PLC

Outseal PLC is a PLC that uses the basic Arduino bootloader base and open source hardware design. The programming language used in Outseal PLC is Ladder diagram. Outseal PLC has two types, namely Outseal PLC

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Nano and Outseal PLC Mega which follow the IEC 61131-2 standard (Bakhtiar, 2020). Figure 4 Outseal PLC Mega V2 Full has 2 serial communication lines that allow Modbus Slave and Modbus Master communication to function together. The Modbus serial communication line used on the Outseal PLC Mega uses an RS485 cable. In this research we used outsealPLC as controller.

D. Proportional, Integral, dan Derivative (PID)

The Proportional, Integral and Derivative (PID) control system is a control method that determines the precision of the instrumentation system with feedback characteristics in the system (A'laa, 2021),There are three ways of setting the PID system, namely P (Proportional), I (Integral), and D (Derivative) controls. In setting the PID control system, it is necessary to make adjustments to the P, I, or D parameters so that the output signal of the system is in accordance with what is desired. The Ziegler-Nichol's PID method can be used to determine the value of proportional gain (Kp), Integral time (Ti), and Derivative time (Td) based on the response characteristics provided by the system (Ogata, 2010). The first Ziegler-Nichol's method when the system response results we get is in the form of an S curve as shown in Figure 2.5, then we can draw a tangent line to get the delay time (L) and time constant (T).

E. Brushless Direct Current Motor (BLDC Motor)

Brushless Direct Current Motor (BLDC Motor) is a synchronous motor that utilizes permanent magnets on the rotor and windings on the stator as a magnetic field. The BLDC motor has a way of working by pulling the permanent magnet on the rotor and pushing it with the stator electromagnetic force which is regulated by the motor driver (Saleh, 2019).

The stator magnet for a BLDC motor has 3 phase windings and a permanent magnet. The position of the BLDC motor rotor can be detected by two methods, namely Sensorless and Sensored. Sensorless is a method that detects by reading the back EMF value generated by the motor, while Sensored is a method that uses a hall effect sensor as a position sensor. The function of detecting the rotor of a BLDC Motor is very important because this position will be used to provide information to the motor driver when it is turned on and the electromagnetic force exerted on the stator.

IV. EXPERIMENTAL RESULTS

This chapter explains the results of the implementation and analysis of the tests carried out at the Materials Testing and Automation Laboratory of the Madiun State Polytechnic. The tests include: (1). Testing the PWM duty cycle signal output on PLC Outseal, (2).Testing and calibration of rotary encoder and anti trap sensor reading, (3.) Reading system characteristics and calculating PID values using the Ziegler-Nichol's method, (4). Testing using the PID method 1 set point, 2 set point, and Multi set point, (5). Testing the Modbus Remote Terminal Unit DCU communication protocol as a Slave using HMI Haiwell and Master to read sensor values from ESP32

A. Testing the PWM duty cycle signal output on PLC Outseal

The primary objective of creating and testing a Door Control Unit (DCU) system for Sliding Door Electric on trains, utilizing a Programmable Logic Controller (PLC), is to investigate the characteristics of the sensors and actuators employed. Through careful analysis, the program on the PLC is tailored to suit these sensor and actuator characteristics. The PWM control test, involving adjustments to the Duty Cycle value within the range of 130 – 150, is conducted to observe and measure the voltage values at various points, such as on the Outseal PLC, PWM to Voltage, and Duty Cycle Value on the Oscilloscope. This value range of 130-150 has been determined as a safe setting for the Brushless Direct Current (BLDC) motor rotation when paired with the Sliding Door Electric. Table 1 show dcu duty cycle test results.

TABLE I. DCU DUTY CYCLE TEST RESULTS

***Duty Cycle* (ppt)**	**PWM *Output Voltage***	***Duty Cycle in Oscilloscope***
130	1,268 V DC	13,00%
135	1,322 V DC	13,60%
140	1,377 V DC	13,90%
145	1,430 V DC	14,15%
150	1,485 VDC	15,00%

Motor speed testing is carried out by changing the value of the Duty Cycle (ppt) issued from the PLC and observing changes in motor speed in RPM units will be carried out. The test is carried out in the range of 135 – 150 ppt. This is done because of the characteristics of the BLDC motor driver. The motor will function if given a voltage above 1.30 V DC and anticipate that the BLDC motor rotates too fast so that it can damage the Sliding Door.

TABLE II. DCU DUTY CYCLE TEST RESULTS

***Duty Cycle* (ppt)**	**Motor Velocity (RPM)**	
	Door Control Unit	***Tachometer***
135	44	37
140	56	45
145	73	61
150	89	73

B. Testing and calibration of rotary encoder and anti trap sensor reading

The Anti Trap system that has been designed in the DCU uses 2 systems, namely based on readings from the calibration results on the ultrasonic sensor and the time on the timer that has been determined according to the standard. The Anti Trap test is carried out by placing an empty bag in the height area which is measured from the top of the door, the test results can be seen in Table III. Based on the results obtained the Ultrasonic sensor can only read the condition if the detected object is < 100 cm, if the object is in a position > 100 cm from the top of the door then the anti trap system remains active using a time reading where the door does not close successfully > 5 seconds.

TABLE III. ANTI TRAP SYSTEM TEST RESULTS

Object distance from the top of the door (cm)	**Object**		
	Bag	**Bottle**	**Hand**
1 – 20	Detected by ulrasonic sensor	Detected by ulrasonic sensor	Detected by timer
21 - 40	Detected by ulrasonic sensor	Detected by ulrasonic sensor	Detected by timer
41 - 60	Detected by ulrasonic sensor	Detected by ulrasonic sensor	Detected by timer
61 - 80	Detected by ulrasonic sensor	Detected by ulrasonic sensor	Detected by timer
81 - 100	Detected by ulrasonic sensor	Detected by timer	Detected by timer
101 - 120	Detected by timer	Detected by timer	Detected by timer
121 - 140	Detected by timer	Detected by timer	Detected by timer
141 - 160	Detected by timer	Detected by timer	Detected by timer
161 - 180	Detected by timer	Detected by timer	Detected by timer
181 - 200	Detected by timer	Detected by timer	Detected by timer

C. Reading system characteristics and calculating PID values using the Ziegler-Nichol's methodts

Retrieval of system characteristic data is carried out using the help of the PLX-DAQ application on a Personal Computer (PC) connected to ESP32 via a serial cable. From the open loop condition data the Sliding Door Electric speed characteristics taken are as follows.

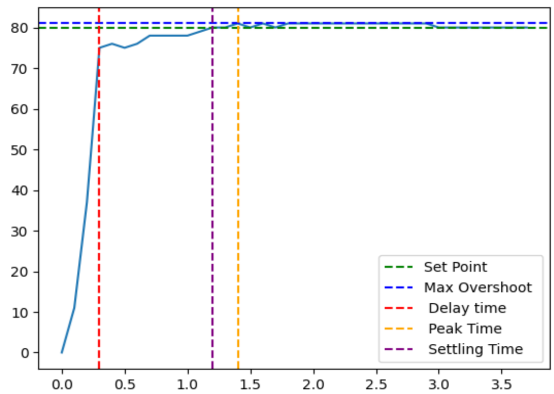

Fig 6. Characteristics of Open Loop Sliding Door Electric

Table IV. *Step Response Open Loop Sliding Door Electric*

(td)	0,1 *s*
(tr)	0,2 *s*
(ts)	1,2 *s*
Overshoot (%mp)	1,25 %

The PID value was determined using the Ziegler-Nichol's method. The system response value forms an S curve and then the tangent line is drawn which then produces the delay time and time constant values. Then the value is entered in the tuning rule table.

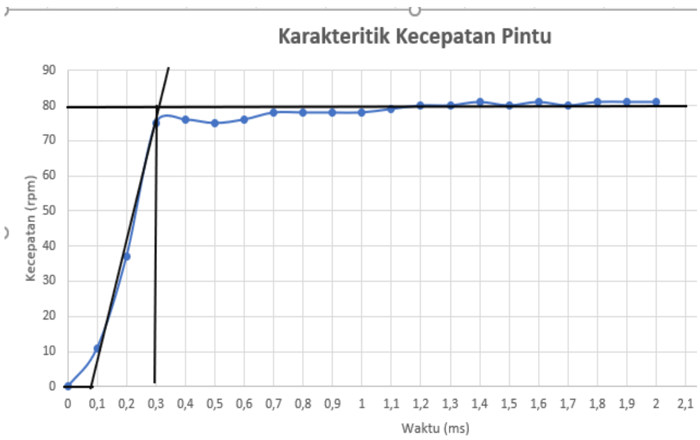

Fig 7. Characteristics of Open Loop Sliding Door Electric

Based on the system response data as shown in Fig 5, the delay time (L) value is 0.1 seconds and the time constant (T) value is 0.2 seconds. Based on these valueswe can determine the values of Kp, Ti, and Td as shown in the table below. So that the value of Kp = 2.4, Ki = 12, and Kd = 0.12 is inputted into the PID value in the program in PLC Outseal using the SETPID and PID libraries. After calculating the values of Kp, Ki, and Kd using the Ziegler-Nichol's method, the next step is to enter these valuesinto the program in the PLC on the Door Control Unit. Test results using ziegler-nichol's PID speed control method. The test results using the Ziegler-Nichol's PID speed control method can be seen in Figure 7

Table V. *Determination of Kp, Ti, and Td parameters*

Control	Kp	Ti	Td
P	$\frac{0,2}{0,1} = 2$	∞	0
PI	$0.9\frac{0,2}{0,1} = 1,8$	$\frac{0,2}{(0.3 \times 0.1)} = 6,66$	0
PID	$1.2\frac{0,2}{0,1} = 2,4$	$2 * 0,1 = 0,2$	$\frac{0,1}{2} = 0,05$

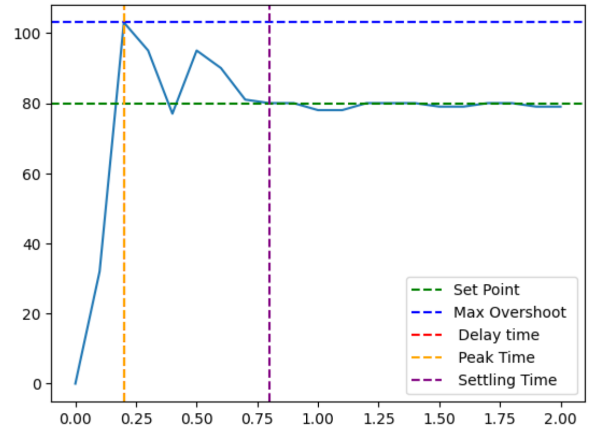

Fig8. Characteristics of Closed Loop Sliding Door Electric

The implementation of the trials carried out on the Sliding Door Electric PID speed control was carried out using 2 set points, this aims to get the door closing time according to the standard. The test is carried out by setting the set point at 85 RPM and 35 RPM, the change in the set point value is based on the distance from the door movement. The speed set point value of 85 RPM will be set if the door movement distance is < 800 mm and the speed set point value of 35 RPM will be set if the door movement distance is > 800 mm. The test results with 2 PID set points can be seen in Fig 8.The results of closing the door lasted 4.2 s and met the standard specified by the Sliding Door Electric speed change chart, which can be seen in Figure 4.21. Based on figure 4.21 the door moves with a set point of 85 RPM for 2.2 s and a change in set point to 35 RPM occurs in 2.3 s.

The speed setting method used in the Sliding Door Electric close loop speed setting uses the ziegler-nichol's method. Before the system characteristics are adjusted using PID control, it takes 1.2s to reach a value that corresponds to the set point. The results obtained with the PID speed setting method are 0.8s, but when using the PID speed setting there is an overshoot of 28.75%. Implementation when the Sliding Door Electric process closes the PID speed setting is implemented using 2 set points and multi set points. Testing using 2 Set Point Sliding Door Electric was able to reach a speed that was in accordance with the change in set point and standard door testing with a time of 4.2s so that the door was closed perfectly. The test using the multi set point speed of the sliding door electric was not able to achieve the changing set point value because the movement of the sliding door electric has a slower response than changes in the set point value, but the time needed for the door to close perfectly still meets the standard with a time of 4.2s.

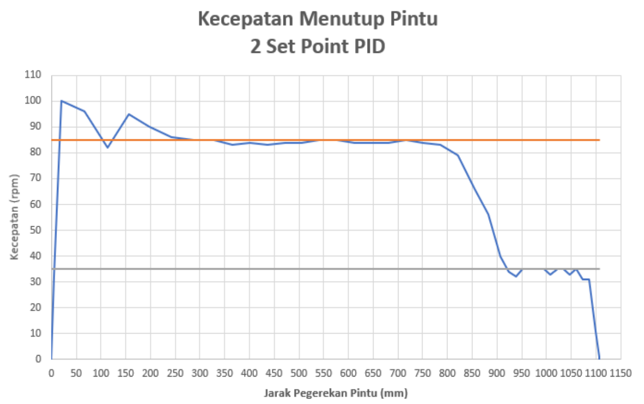

Fig 9. Characteristics of PID 2 set point graph based on the distance of the door movement

D. Testing the Modbus Remote Terminal Unit DCU communication protocol as a Slave using HMI Haiwell and Master to read sensor values from ESP32

Configuration of the Door Control Unit is carried out using the Modbus RTU library provided by PLC Outseal. In the implementation and testing carried out in research using the Door Control Unit as a master, it is done by reading and writing data to the slave.

The communication protocol design for the DCU employs the Modbus RTU communication protocol. Critical parameters for configuring the DCU as a master on Modbus RTU are the Baudrate and Slave Number settings. Ensuring consistency in these settings is crucial as any discrepancies can lead to communication failure with the slave device, such as the ESP32 in this research.

In the DCU's Outseal PLC programming, the MF4 library (Read Input Register) is utilized for reading integer variable values sent by the slaves (e.g., ESP32). On the other hand, the MF6 library (Write Single Register) serves to write values into variables on the slave device. By using the Outseal PLC as the master, the DCU can seamlessly integrate with sensors having individual reading modules through the Modbus RTU protocol.

For the DCU to function as a slave, it is configured with Baudrate set at 9600 and a slave address of 13 during the program upload to the PLC. The Modbus RTU variable settings for the DCU as a slave adhere to the standards defined by the Outseal PLC. Consequently, the DCU can effectively read and write Boolean and Integer values through the master controller (HMI or PLC).

The versatility of the Outseal PLC-based DCU in functioning as both master and slave enables its implementation on trains. By receiving commands from the TCMS via the Modbus RTU RS485 protocol, the DCU can effectively control the opening and closing of doors, enhancing train operation and safety.

V. CONCLUSIONS

Based on the conducted design and testing in the thesis titled "Design of a Rolling Stock Door Control Unit (DCU) Based on Programmable Logic Controller (PLC)," the following conclusions can be derived:

The Outseal PLC proves to be a suitable main control device for Door Control Unit (DCU) products due to its diverse capabilities, including reading digital input sensors, digital output, PWM output settings, and supporting Modbus RTU RS 485 based communication protocols. Leveraging these capabilities, Outseal PLC-based DCUs can be integrated with a wide range of actuators and sensors, encompassing both those controlled directly and others that require communication protocols for control.

The Outseal PLC-based Door Control Unit effectively facilitates a close loop control system utilizing the PID control method. Employing the SETPID and PID libraries found in the Outseal Studio application, the PID method used in the research is the Ziegler-Nichol's method. The obtained PID parameters are Kp = 2.4, Ki = 12, and Kd = 0.12. Through the PID speed control method, the conducted tests produced the following results: delay time = 0.2s, rise time = 0.1s, steady time = 0.8s, overshoot (%mp) = 28.75%, and steady time error = 1%.

The Outseal PLC-based Door Control Unit demonstrates the capability to operate as both a master and a slave in the Modbus RTU RS485 communication protocol. In its master role, the DCU can be seamlessly integrated with sensors or actuators that necessitate control via Modbus RTU communication. Conversely, functioning as a slave, the Modbus RTU DCU can be effectively controlled by the primary control device within a train, receiving commands such as open, close, and anti-trap detection.implementation of the trials carried out on the Sliding Door Electric PID speed control was carried out using 2 set points, this aims to get the door closing time according to the standard. The test is carried out by setting the set point at 85 RPM and 35 RPM, the change in the set point value is based on the distance from the door movement. The speed set point value of 85 RPM will be set if the door movement distance is < 800 mm and the speed set point value of 35 RPM will be set if the door movement distance is > 800 mm. The test results with 2 PID set points can be seen in Fig 8.The results of closing the door lasted 4.2 s and met the standard specified by the Sliding Door Electric speed change chart, which can be seen in Figure 4.21. Based on figure 4.21 the door moves with a set point of 85 RPM for 2.2 s and a change in set point to 35 RPM occurs in 2.3 s.

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