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Digital PID Trainer Based On Arduino For DC Motor Speed Control With Ziegler Nichols Method

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A B S T R A C T

This research aims to design and implement a Proportional Integral Derivative (PID) control system to regulate the speed of a DC motor using the Ziegler Nichols tuning method, focusing on improving the stability and responsiveness of the system for industrial automation applications. The research uses a mathematical model of a DC motor derived from its electrical and mechanical components for simulation and analysis of the system behavior. The PID controller is implemented with the Ziegler Nichols tuning method (open and closed loop) to determine the optimal parameters (Kp, Ki, Kd). The system was tested using Arduino, L298N motor driver, and MATLAB for simulation and analysis. Performance is evaluated based on response characteristics such as rise time, settling time, overshoot, and steady state error. The Ziegler-Nichols method successfully tuned the PID controller with optimal parameters Kp = 11.7, Ki = 1, and Kd = 0.25. Analysis of the system response shows rise time = 0.4866 s, settling time = 2.5829 s, overshoot = 19.6194%, and steady state error = 0.0861%. This PID-controlled system provides fast response and good stability, with significant improvement in reducing steady state error and overshoot compared to systems without controllers or those using trial-and-error tuning. The Ziegler-Nichols tuning method is effective for optimizing PID control in DC motor speed regulation. The proposed system offers a reliable and efficient solution for industrial applications that require precision motor control.

INTRODUCTION

Technological developments in the field of automation control have designed various systems that can be applied in industry, one of which is the use of DC motors. DC motor is a type of electric motor that is able to convert direct current electrical energy into mechanical energy between interacting magnetic fields and currents. The control system is simpler because it only needs to adjust the voltage or current value to change the desired speed [1]. DC motor control can be regulated by various methods, fuzzy methods can be used to control the rotation of DC motors [2]. Control in fuzzy using the rules that apply to the fuzzy method can minimize errors in the system and can increase efficiency by utilizing existing logic rules [3][4]. However, the weakness in fuzzy is in the form of giving very free choices, making it difficult to manage the system.

PID control method is an effective method for regulating the speed of DC motors. Its ability to minimize error and very fast response is the right step for implementation in the use of DC motors [5]. PID parameters that can be adjusted easily make it possible to study the effect of each parameter (proportional, integral, and derivative) on system response directly, both in simulation and direct use of training tools [6][7].

Based on existing problems, the use of PID controllers to control DC motor devices by adjusting angular velocity and Ziegler Nichols tuning to get a better response [8]. Where the transfer function becomes an important part in the PID controller to regulate the speed of the DC motor with the input sourced from the voltage and the output obtained in the form of speed on the DC motor [9]. In research [10] using PID controllers to drive stepper motors in the microplastic molding process. In this study, a good mold was obtained in giving the PID value to drive the stepper motor. The performance characteristics of the PID in the form of using the error value obtained for the existing learning method to improve the value.

The use of digital PID in driving DC motors has a high level of effectiveness, this is because the method used is able to provide control that is responsive to changes in acceleration in DC motors. By adding the Kp parameter value, it can minimize the steady-state error, adding the Ki parameter value can make the overshoot increase, and by adding the Kd parameter value, it can minimize the overshot obtained by the system [11][12].

In research [13] designed the manufacture of DC motor training tools (trainers) using PID (Proportional, Integral, Derivative). This research gets the results expected by the designer, but it is not proven by the mathematical model obtained from the results

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of the DC motor control obtained. The mathematical model is obtained by knowing important variables such as armature resistance (Ra), inductance (La), rotor angular speed (ω), and torque (T) [14]. This model includes important motor parameters such as armature resistance, inductance, back electromotive force (emf), and moment of inertia, which are then used to simulate the motor dynamics for speed [15].

The use of the Ziegler Nichols method in controlling DC motors is very effective for obtaining good system stability against a given set point [16]. The DC motor will continue to adjust its system stability even though the set point value continues to change based on the load given [17]. The Ziegler Nichols method controller is able to provide a good system response analysis, starting from overshoot, rise time, settling time, and steady state error. A good system response analysis makes the DC motor have excellent system stability based on the given values of the P parameter, I parameter, and D parameter. This is evidenced by the research that has been done by displaying good system response results on DC motors in their application in a system [18][19][20].

DC motor control is also often controlled using fuzzy methods by applying various fuzzy logic to regulate the speed of DC motors. In research [21] displays a graph of simulation results showing that the higher the pressure value received by the piezoelectric sensor, the faster the motor rotates, according to the settings generated by fuzzy logic. The simulation results show that the system works well in controlling the motor speed based on input from the piezoelectric sensor.

The Ziegler Nichols method can also be applied to AC motors that have alternating polarity. AC motors that have speed instability when given different loads become an obstacle in this system. The use of the Ziegler Nichols method in this problem is a good solution based on the research that has been done. The AC motor is able to oscillate very well until it reaches stability at the set point value given to the system [22].

The difference between this research with the previous research is that in this research, the product can be used by the students to compare the results between simulation and the PID Trainer.The simulation is conducted using Matlab. The Simulink in Matlab can be connected to Arduino.

The advantages of this research compare to previous research is that the function transfer is already obtained. So the students can apply the controller in Matlab and in the trainer to see the results in both simulation and trainer. But, this research has its own limitations. Because it can only be applied to DC motor. It cannot be applied ini AC motor. The tuning Methods can also using different type of tuning such as Cohen Coon and Chien Methods.

METHODS

Mathematic Model of DC Motor

The mathematical model is obtained from the output generated in the DC motor based on two main parts in the electrical part and the mechanical part of the DC motor. DC motors are capable of producing consistent torque at a speed that adjusts to the applied voltage and a separate gain that is able to maintain a speed that is almost fixed at a given constant voltage [23][24]. The electrical equations in DC motors consist of a voltage source, armature resistance, armature inductance, armature current, and back EMF [25]. The equation attached to equation 1 is basically in the form of:

$$E_a = R_aI_a + L_{a dIadt} + E_b \qquad 1$$

The back-motion force Eb is directly proportional to the angular velocity of the rotor, which is expressed in the equation 2

$$E_b = K_{b d\theta dt} \qquad 2$$

For the mechanical part, the following equation is used based on Newton's law of dynamics in equation 3

$$J_m d^2\theta_{dt2} + B_{m d\theta dt} = T_m \qquad 3$$

The torque Tm produced by the motor is proportional to the armature current Ia and torque constant Kt, so equation 4

$$T_m = K_tI_a \qquad 4$$

By combining the above electrical and mechanical equations, through the substitution method and the application of Laplace transform, the differential equation for the DC motor model is simplified to a transfer function between the input voltage Ea(s) and the output angular velocity θ(s) denoted by equation 5.

$$\frac{\theta(s)}{Ea(s)} = \frac{Kt}{JmLaS^3+(JmRa+BmLa)S^2+RaBmS+KtKbS} \qquad 5$$

Proportional, Integral, Derivative (PID)

The PID control system is a close loop system or uses a feedback method in its working system. PID control consists of 3 interrelated parameters in the form of Proportional (P), Integral (I), Derivative (D). The three parameters have their own advantages in their application to the resulting output in reducing system errors. PID is used by combining the three PID parameters in order to maximize the work of the system to achieve the best setpoint with a given parameter value and the constants used in the PID control system in the form of Kp, Ki, and Kd [26].
The transfer function equation used is as follows:

$$U(t) = K_pe(t) + K_I\int_0^t e(t)dt + K_D\frac{de(t)}{dt} \qquad 6$$

The PID controller will be implemented on the system to be used as a controller by inputting the value of the parameters used in the PID controller based on equation 6, so that the system will respond to the response of the input that has been given. Responses need to be designed in accordance with the wishes based on the system designed to be able to get maximum results with performance characteristics to improve system output and be able to achieve setpoints with good performance [27]. The system response can be determined using the Laplace second-order system closed-loop transfer function equation with the following equation 7:

$$\frac{Y(s)}{X(s)} = \frac{\omega n^2}{s^2+2\zeta\omega ns+\omega n^2} \qquad 7$$

Parameter P can reduce the rise time of the system but can increase overshoot and cannot eliminate the steady state error. steady state error. The Integral (I) parameter is able to eliminate the steady state error value and increase the rise time. state error and increase rise time, but the the resulting overshoot increases. Parameter D is able to increase the stability of the system and minimize the system overshoot value [28]. The PID controller has

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a frequency domain in its system control, the frequency domain in the PID controller is more directed at analyzing the system response control system response to input signals in various frequencies. Frequency domain aims to study the characteristics of the system response to various input frequencies, such as stability and phase margin. System stability can be analyzed by PID controllers in the form of measurements obtained from the gain margin by showing how much the gain can be increased before the system becomes unstable, phase margin by measuring how much the phase can change before the system reaches instability, then there is a bandwidth with a frequency range where the system can react well to changes in the input of the system. Generally, the minimum recommended gain value to maintain system stability is more than 6 dB and the minimum recommended phase margin value to maintain system stability is more than equal to 30 degrees in order to get a safe response to phase changes and low risk of experiencing excessive oscillation or instability [29].

Ziegler Nichols Method

Ziegler Nichols is a method used for system adjustment and control by adjusting the value of PID control parameters in automated systems. Ziegler Nichols tuning is used to obtain fast and stable response values in the control system. Ziegler Nichols tuning is applied to find the optimal value of three PID parameters in the form of Kp (proportional gain), Ti or Ki (integral time constant or integral gain), Td or Kd (derivative time constant or derivative gain) [30]. This tuning has the first method with an open loop system with the system will be run without a feedback system based on table 1:

Table 1. Ziegler Nichols Open Loop

Pengendali	Kp	Ti	Td
P	$\frac{T}{L}$	∞	0
I	$0.9\frac{T}{L}$	$\frac{L}{0.3}$	0
D	$1.2\frac{T}{L}$	2L	0.5L

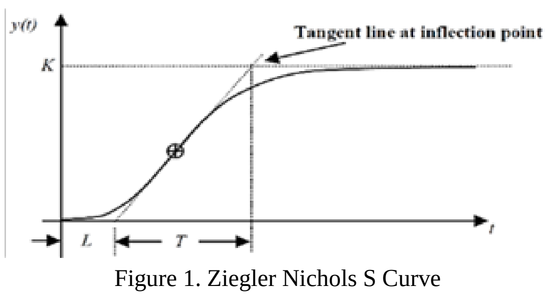

Figure 1. Ziegler Nichols S Curve

In figure 1 there are 2 Ziegler Nichols parameters in the form of L (time delay) or time delay with the time when the system begins to respond after being given an input value and T (rise time) or rise time with the time required for the system to reach system stability. The inflection point obtained on the curve shows where the acceleration of changes in system output is maximum, at this point also the occurrence of a tangent line described by its intersection with the time axis helps find the parameters L and T. The value of the constant K or gain shows the final response of the system to achieve stability.

The second Ziegler Nichols method is a close loop system to obtain optimal and stable PID tuning. This method starts by setting the Kp (proportional) value only, with integral = ∞ and derivative = 0. The value of Kp is gradually increased from a value of 0 to a critical value so that the system begins to oscillate continuously with the amplitude obtained constant. Two important parameters in the second method are obtained from this oscillation with Ku being the value of Kp when the continuous oscillation occurs, and Pu being the time period of the continuous oscillation [31].

Table 2. Ziegler Nichols Close Loop

Pengendali	Kp	Ti	Td
P	0.5Ku	∞	0
I	0.45Ku	$\frac{1}{1.2}$Pu	0
D	0.6Ku	0.5Pu	0.125Pu

In table 2 using the second method in Ziegler Nichols tuning is able to provide more precise and stable results on the system, this is because the system uses a closed method and uses feedback [32].

Schematic System

The system schematic design will be designed on each component used in this research. After the process of testing each component, of course, it will connect all the components that have been tested to make a unified system in this study. The schematic design in figure 2 explains the relationship between components in one system.

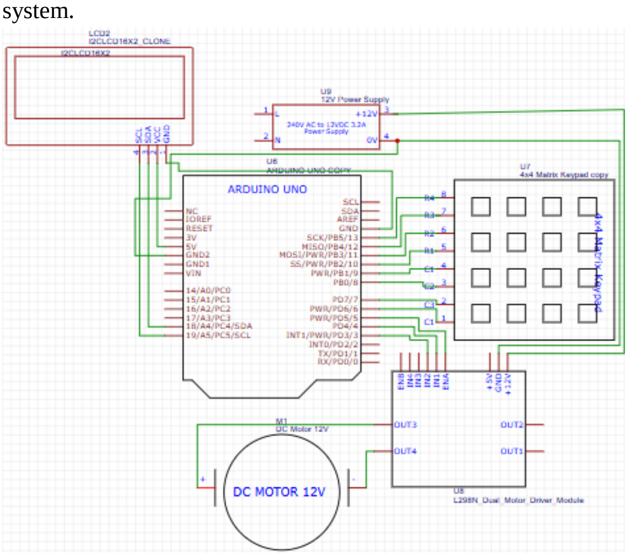

Figure 2. *Schematic System*

Figure 2 explains the interrelationship between components into one system used in this research. Arduino Uno is used as the microcontroller of this system which is interconnected with the L298N driver, 12 V adapter, 4x4 keypad, and 16x2 I2C LCD. So that the design and assembly of the tool will be in accordance with the schematic design that has been made according to figure 2. The system schematic circuit is designed using EasyEDA to simplify and clarify the circuit of each interconnected component in the system.

System Flow

The system in this research is shown in figure 5 which shows how the process works from the beginning of entering the PID parameter value until the system starts running based on the given PID value.

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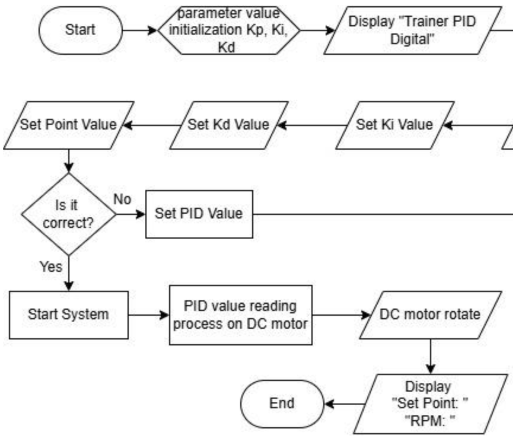

Figure 3. System Flow

Figure 3 shows the flow of the system running, starting with the PID parameter value initialization process and the system will continue by waiting for the process of providing PID parameter values (Kp, ki, and Kd) and setpoint values as a threshold for the movement of the DC motor speed. The system will ensure that the PID parameter values entered are in accordance with the PID parameter values to be tested, the PID parameter values that have been inputted to the system will be processed by the Arduino to rotate the DC motor. The DC motor will rotate based on the PID parameter value received to adjust its speed, this speed value will be displayed by the LCD in real-time.

Based on [33], the requirement for the trainer must allows users to apply various input signals to the PID controller and monitor the system's response using an oscilloscope. This hands-on method helps learners grasp how PID controllers manage system behavior, making it a valuable tool for students, researchers, and control engineering professionals.

With a built-in setpoint adjustment feature, the trainer must enable users to explore different control scenarios. It also supports integration with multiple feedback systems, allowing for deeper analysis and examination of control strategies.

RESULTS AND DISCUSSION

The research process is carried out by testing the performance and analyzing the results obtained on the DC motor. The parameters used in this test are without a controller, using a controller (trial error), and using the Ziegler Nichols method controller. The results of the parameters obtained in the form of tuning graphs and analysis of system responses (time rise, settling time, overshoot, steady state error) of DC motors obtained using Matlab.

Without Controller Analysis

The first test was carried out by providing varying voltages to the DC motor and recording the resulting RPM value.

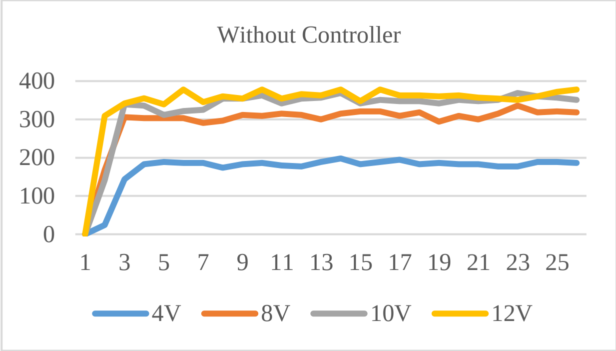

Figure 4. System Without Controller

Based on the results of the test data obtained through figure 4 displays a graph of the response obtained from the DC motor without a PID controller. The response obtained is a collection of responses carried out in the test based on the voltage value given to the DC motor. The DC motor will rotate according to the voltage value given, in this test using a PWM value that varies by showing the appropriate voltage value to regulate the speed of the DC motor. The value given is a maximum of 255 PWM adjusting to the PWM specifications owned by Arduino of 8 bits. The results obtained show that the DC motor successfully rotates according to the voltage value given, the speed obtained by the DC motor is the lowest when given a voltage of 4V and the speed will rotate maximally when the DC motor is given a voltage of 12V and produces a DC motor rotation at 380 RPM. The DC motor does not rotate and will produce a buzzing sound only when the given voltage condition is lower than the voltage value of 4V. The method without a PID controller shows that giving a set point to this DC motor is not effective, this is because the DC motor rotates based on the given voltage conditions. Thus, recalibration is required when the RPM obtained on the DC motor changes.

System With PID Controller (Trial and Error Method)

The PID controller system using the trial and error method is carried out to find out the results obtained when inputting the PID parameter values with arbitrary values without any other method rules. The results of testing the PID controller trial and error method are in figure 5.

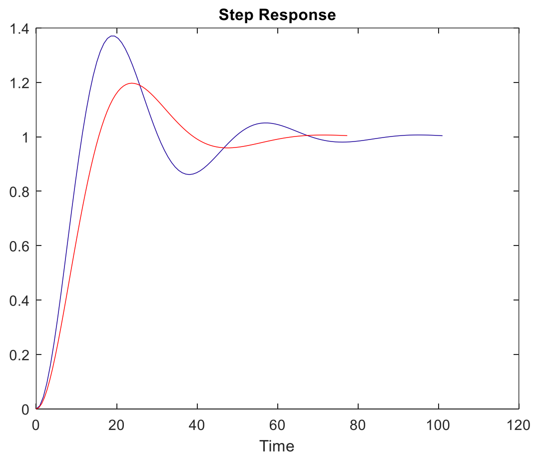

Figure 5. PID Controller (Trial and Error Method)

The data results obtained in figure 5 show a graph of the tuning results obtained by the DC motor when given different PID parameter values. In the red colored curve (PID 1) on the graph

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using the PID parameter value with the value of Kp = 1.5, Ki = 0.3, Kd = 4, Set Point = 250 RPM and the blue colored curve (PID 2) using the PID parameter value with the value of Kp = 1, Ki = 0.3, Kd = 0.5, Set Point = 250 RPM. The trial and error method is used to determine the system response obtained by the DC motor when giving the PID parameter values with free values without any other rules. Based on the tuning results obtained in the form of graphs, the analysis of the response results obtained in table 3 shows the value of the rise time, settling time, overshoot, and steady state error.

Table 3. Respon Analysis System

PID Controller				
	Time Rise (s)	**Time Settling (s)**	**Overshoot (%)**	**Error Steady State (%)**
PID 1 (Red)	14.1830	55.4797	9.7877	0.3475
PID 2 (Blue)	9.8578	66.5416	23.7570	0.0446

The response analysis in table 3 shows the system response obtained from 2 different PID parameter values using the trial and error method. PID 2 has an advantage in terms of time rise with a value of 9.8578 seconds which shows that the system is able to touch the initial set point value in a fast time compared to PID 1 with a time of 14.1830 seconds. The fastest settling time is obtained by PID 1 by taking 55.4797 seconds to achieve system stability, while PID 2 is relatively longer to achieve system stability with the time obtained for 66.5416 seconds. The overshoot obtained in PID 1 is lower by 9.7877 compared to the overshoot owned by PID 2 of 23.7570, this shows that PID 1 is more stable by producing small oscillations. While the steady state error owned by PID 2 is lower by 0.0446% than the steady state error owned by PID 1, this shows that PID 2 has a high level of accuracy in reaching the set point. Based on the results of the system response analysis obtained, PID 1 has a better system stability response rate than PID 2, this is because PID 1 has a lower overshoot and settling time than PID 2. Thus, PID 1 is more advantaged because it is more stable and faster to achieve stability in the system with a set point value that is used as a system goal.

Ziegler Nichols Open Loop Method

Figure 6 shows the response obtained by the DC motor when given a voltage of 12V. This aims to find the T and L values possessed by the DC motor when given the maximum voltage in the form of an S curve.

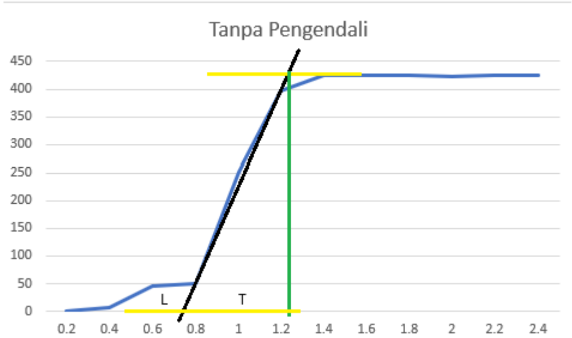

Figure 6. Ziegler Nichols S Curve

The S Curve in figure 6 shows the response of the system to a step input, where the system begins to respond to changes in input and gradually reaches a stable state. The S curve in figure 6 starts to deviate from the initial value at a certain point which indicates the start of the system response. The time obtained from when the step input is given until the curve starts to rise is the dead time value (L) and the system takes a certain time to reach 63.2% of the steady state value is the time constant value (T). Based on the S curve obtained, the value of L = 0.78 seconds and the value of T (1.21 - 0.78) = 0.43 seconds. The L and T values will then be implemented on the Kp, Ki, and Kd parameter values in the open loop system. The open loop PID parameter values are shown in table 4 by entering the previously obtained L and T values.

Table 4. Parameter PID Open Loop

Parameter	**Kp**	**Ki**	**Kd**
P	0.5512820	∞	0
PI	0.496154	2.6	0
PID	0.6615384	1.56	0.39

In table 4 there are 3 PID parameters with values obtained based on the previous L and T values. In this open loop system, the system has 3 PID parameter values that will be tested. This test includes P parameters, PI parameters, and PID parameters. The test results of these three parameters will be carried out in the form of graphs and also analysis of the system response obtained. The test results obtained from the three PID parameters of the open loop Ziegler Nichols method are in figure 7.

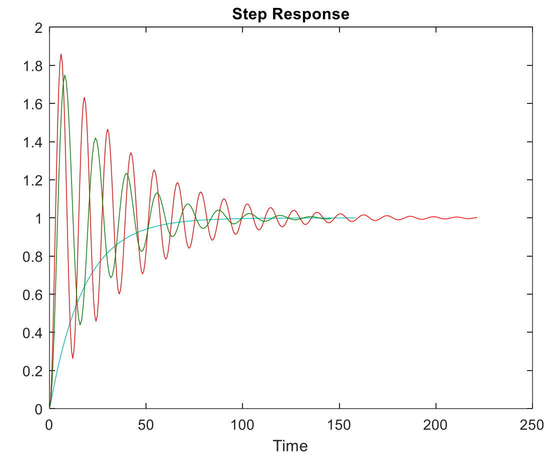

Figure 7. PID Controller Ziegler Nichols Open Loop Method

Figure 7 shows the response of the system to step input using the Ziegler Nichols tuning method in the open loop for three different control parameters, the P parameter is represented by a blue colored curve, the PI parameter is represented by a red colored curve, and the PID parameter is represented by a green colored curve. The curves in figure 7 show that the open loop system produces an oscillating system before it is fully stabilized. This shows that the DC motor continues to calibrate to reach the set point value as quickly as possible.

Table 5. Parameter PID Open Loop Result

PID Controller				
	Time Rise (s)	**Time Settling (s)**	**Overshoot (%)**	**Error Steady State (%)**

P	37	67	0	0
PI	2.8718	105.0460	73.1392	0.8127
PID	3.1010	105.0061	69.3938	0.7090

Table 4 shows the results of the system response analysis of the DC motor when given three different parameter values. Parameter P has a fast response time that only takes 37 seconds before it is in a stable state even though there is no overshoot and steady state error. The results obtained in the P parameter are less effective for systems that require fast response without a mechanism to reduce steady-state error and overcome oscillations effectively resulting in unbalanced performance. The PI parameter has an increase in rise time, but has a relatively long settling time to achieve system stability with a high overshoot of 73.1392 which results in the system continuing to oscillate before reaching stability with a steady state error of 0.8127%. While the PID parameter is the best parameter from the previous parameter based on the results of the system response analysis obtained. PID parameters have a value towards fast stability, low overshoot and low steady state error. PID provides balanced control between system response speed and system stability in DC motors.

The function of a mathematical model of a DC motor in the context of a PID control system using the open loop Ziegler-Nichols method is to provide an accurate mathematical representation of the dynamic behavior of a DC motor. This model makes it possible to analyze, predict, and optimize the system response before applying the PID controller. The mathematical model used in this method to obtain the appropriate tuning results from the transfer function obtained using the following Laplace second order:

$$\frac{0.1573}{s^2 + 0.07282\,s + 0.1573} \quad (8)$$

The mathematical model is obtained from system identification which will be used in the transfer function to obtain tuning results based on the given PID parameter valus.

Ziegler Nichols Close Loop Method

The Ziegler Nichols close loop method requires the Ku and Tu values to obtain the PID parameter values (Kp, Ki, Kd) used to analyze the system response obtained. To find Ku itself by looking for the Kp value slowly to get a system response that continues to oscillate stably with the condition that the Ki and Kd parameter values are given 0. When the DC motor gets the right Kp value by showing a stable oscillating system response, the Kp value is used to become the Ku value. While the Tu value is obtained by looking at the time it takes for the meeting point between peaks when the system oscillates stably. In this study, the Ku and Tu values were obtained through figure 8 which indicates that the system oscillates stable.

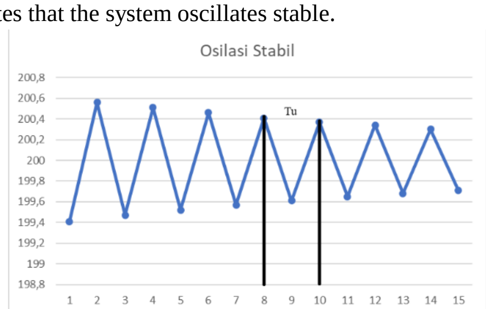

Figure 8. Sistem Berosilasi Stabil

In figure 8, the system shows stable oscillations with a value of Kp = 19.5. So the Ku value used in this open loop method is 19.5. In addition, the time obtained from the meeting point between peaks is 2 seconds, so the value of Tu = 2.

Based on the search for the Ku and Tu values that have been found, these values can be implemented with the close loop PID parameter values in table 5.

Table 6. Parameter PID Close Loop

Parameter	Kp	Ki	Kd
P	9.75	∞	0
PI	8.775	1.6	0
PID	11.7	1	0.25

In table 6, there are PID parameter values for the Ziegler Nichols close loop method from the calculation results obtained based on the Ku and Tu values. These three parameter values are used in this study to determine the performance of the DC motor system when using the Ziegler Nichols close loop method. The test results obtained from the three PID parameters of the Ziegler Nichols close loop method are in figure 8.

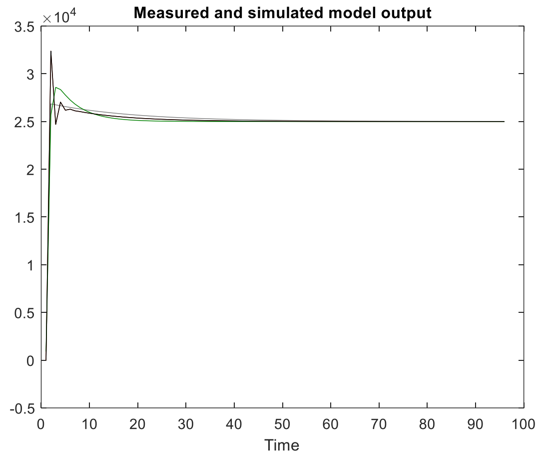

Figure 8. PID Controller Ziegler Nichols Close Loop Method

Figure 8 shows the graphical results obtained when the P parameter, PI parameter, and PID parameter values are run. The P parameter curve is represented in blue, the PI parameter curve is represented in green, and the PID parameter curve is represented in black. The graphical results obtained show that the P parameter does not show oscillations in the system, while the PI and PID parameters show oscillations when the DC motor is first run. The results of the system response analysis obtained from the results of the graph are in table 7.

Table 7. Parameter PID Close Loop Result

PID Controller	Time Rise (s)	Time Settling (s)	Overshoot (%)	Error Steady State (%)
P	1.4	2	0	0
PI	0.8279	9.2035	7.3119	0
PID	0.4866	2.5829	19.6194	0.0861

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Based on the results of the system response analysis obtained in table 7 shows the results of each PID parameter after running. The P parameter takes 1.4 seconds to touch the starting point of the set point and takes 3 seconds to reach stability. The PI parameter takes 0.8279 seconds to touch the set point value and takes 9.2035 seconds to reach stability with an overshoot of 7.3119. The PID parameter has a better and faster time than the previous parameter response results. Of course, this is evidenced by the PID parameter only takes 0.4866 seconds to touch the set point value and takes 2.5829 seconds to achieve system stability with a realtif large overshoot with a value of 19.6194 accompanied by a steady state error of 0.0861%. From the results of this analysis, the PID parameter provides the best results because it has the fastest response speed with the fastest rise time and settling time. In addition, PID shows the best level of accuracy with the smallest steady state error compared to other parameters. Although the overshoot of PID is higher, it is still acceptable because the system is able to reach steady state faster.

Based on the requierement, it can be concluded that the end products has meet the requirement. Overall, the students can see the response of the system using various mode of controller. The students can compare the results with the optimum results from ziegler Nichols tuning mode.

CONCLUSIONS

This research proves the use of the Ziegler Nichols method to control the speed of a DC motor gets better results and has a fast response. This test is done by comparing the system without using PID controller, system using PID trial and error method, and system using PID controller Ziegler Nichols method. The results show that the Ziegler Nichols method PID controller has excellent response analysis results compared to no PID controller and using the trial and error method PID controller. The best PID parameter values are obtained with Kp value = 11.7, Ki value = 1, and Kd value = 0.25 and the best response analysis results with rise time only takes 0.4866 seconds, settling time only takes 2.5829 seconds, overshoot of 19.6194 and a small steady state error of 0.0861%. Overall, using the Ziegler Nichols method PID controller has the potential for a very fast response to obtain stability and high accuracy in the system. It is hoped that further research can be carried out using additional speed sensors to get more specific values.

There is still limitations that can be improve in the next research. The motor type can also used AC motor. On the other hand, the tuning methods can also use Cohen coon and chien Methods other than Ziegled Nichols tuning methods.

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