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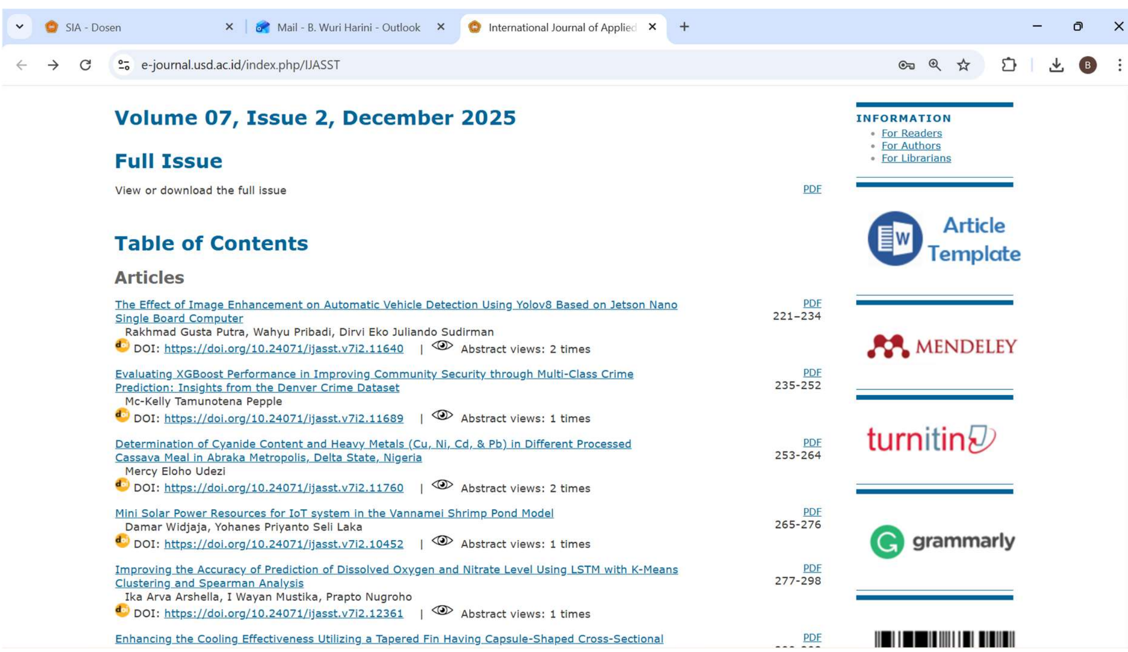
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Design of a Speed Sensorless Control System on a DC Motor using a PID Controller

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Abstract
The speed sensorless control system on a DC motor is a DC motor speed control system that does not use a speed sensor to measure the motor speed. The motor speed value is estimated by an observer from the stator current and voltage that are measured using a sensor. This study uses an *R* observer method. The difference between the estimated speed and the reference speed is then used by the PID controller to adjust the motor speed to match the desired reference speed. PID parameter tuning using heuristic method. With a setpoint of 6800 RPM and using a combination of $K_P = 0.5$, $K_I = 0.05$, and $K_D = 0.34$, a speed value of 6792.76 RPM was obtained. Sensorless motor speed control using a PID controller produces an optimal system with a low Steady State Error (SSE) value of around 0.1%, very small oscillations of 0.39%, a fast rise time of 4 seconds, and a fast-settling time of 6 seconds.

Keywords: DC motor, Heuristic tuning, Observer, PID controller, speed sensorless

1 Introduction

Speed control of a DC motor is an important aspect in various control system applications, such as robotics, industrial automation, and electric vehicles. Typically, speed control systems use sensors such as encoders to obtain speed feedback. However, the use of sensors increases the system's cost, complexity, and vulnerability to physical or environmental disturbances. Therefore, alternative approaches are needed that can accurately estimate speed without directly using speed sensors. The system that doesn't use a sensor to measure the controlled variable is a sensorless control[1][2].

Observers or estimators are commonly used solutions to replace sensors in closed-loop control systems. To estimate motor speed, there are several observers that can be used, for example, Model Reference Adaptive System (MRAS)[3], Luenberger [4], Extended Kalman Filter (EKF)[5], and Sliding Mode Observer (SMO) [6]. These methods use complex algorithms. By utilizing a mathematical model of the system and input data such as voltage and current, the observer can estimate internal variables such as motor speed more simply [7]. In previous research, two observer methods have been proposed to estimate the speed of a DC motor. The two methods are the *R*-method observer and the *L-R* method[8]. In that study, the performance of the *L-R* method is better than the *R*-method. In this study, both observers will be applied to estimate the speed of a DC motor that is different from the DC motor in the previous study. From the two observer methods, the method that can estimate the speed of the DC motor with the least error will be selected.

The estimated results are then compared to a reference speed. The difference between the two values is then controlled using a controller. This study uses a PID (Proportional-Integral-Derivative) controller [9]. PID was chosen because it is a mature controller. PID controllers have proven reliable in controlling closed-loop control systems. The purpose of a PID controller is to maintain a stable motor speed at a desired value (set point). The combination of an observer and a PID controller is expected to provide responsive, accurate, and efficient control performance without the need for physical sensors. Some researchers use PID controllers to control DC motor speed in sensorless speed control systems. However, these systems use EKF observers[10]. Others use sensorless motor speed control using Integral Proportional (IP) speed controllers[11].

The PID controller has three parameters that must be determined. They are Proportional gain (K_P), Integral gain (K_I), and Derivative gain (K_D). In this study, the heuristic tuning method will be used to determine the PID controller parameter values. This method was chosen because it has been proven to be able to determine the controller parameters well [12]. In this study, it will be investigated whether the PID controller is able to control the speed of a DC motor in a sensorless control system that uses the *L-R* or *R* method observer properly.

2 Materials and Methods

The block diagram of the sensorless speed control system on the DC motor used in this study is shown in Fig. 1. The system consists of a DC motor, INA 219 current and voltage sensors, an observer, a controller, and a driver. The main circuit of this sensorless speed control system is shown in Fig. 2. The INA 219 current and voltage sensors measure the stator current and voltage. These currents and voltages are used to estimate the motor speed. This estimated speed is then compared to the reference speed. The difference between the two is called the error. A PID controller will calculate the controller output from this error input, which will be used to regulate the motor speed so that the motor speed will be the same or close to the reference speed. All calculations are performed by the Arduino Uno microcontroller. This study used variable DC power supply.

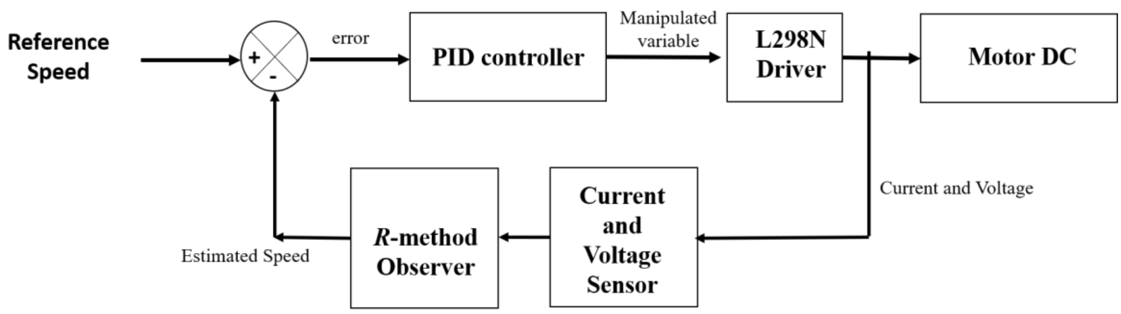


Figure 1. The block diagram of the sensorless speed control system on the DC motor using a PID controller

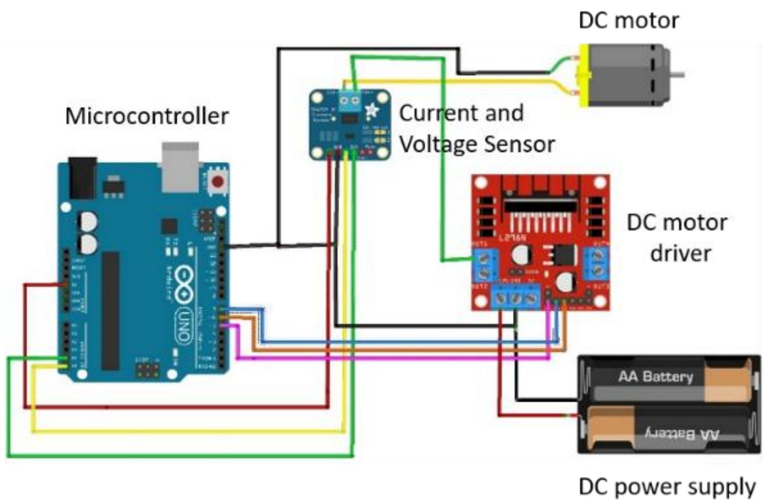


Figure 2. The main circuit of speed sensorless control of DC motor[8]

This sensorless speed control system does not use a speed sensor to measure the DC motor speed directly from the rotor rotation. The speed is estimated from the results of stator current and voltage measurements. Therefore, this system does not use a speed sensor, but uses current and voltage sensors, which are then calculated by the observer into an estimated speed signal.

Two observer techniques were put out in earlier studies to measure a DC motor's speed without the need for a speed sensor. The R-method observer and the L-R method observer are the suggested approaches [8]. Both of these techniques use the DC motor electrical equation to estimate a DC motor's speed. Equation 1 expresses the DC motor electrical circuit as the current passing through the resistance and inductance of the armature winding[13].

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \tag{1}$$

where e_a is the back emf, L_a is the armature self-inductance brought on by the armature flux, R_a is the armature resistance, i_a is the armature current, and v_a is the armature supply voltage. Equation 1 can be used to determine the motor's resistance and inductance values, and equation 2 can be used to determine the armature voltage and current values to determine the back emf value (e_a).

$$e_a = v_a - (R_a i_a + L_a \frac{di_a}{dt}) \tag{2}$$

From the equation above, if the motor parameters (resistance and inductance) are known from previous tests, and the current and voltage are measured at any time using current and voltage sensors, then the back emf value can be calculated. The back emf value is proportional to the angular velocity of the rotor. It can be calculated using equation 3.

$$e_a = k_E \omega_m \tag{3}$$

Therefore, if the value of k_E has been obtained from the previous test, then the motor speed can be calculated from the equation. The difference between the R and L-R observer methods is that if L-R calculates the back emf value with equation 2, then the back emf value for the R observer method is obtained with equation 2, but the L value is ignored.

In this study, the difference between the reference speed and the estimated speed, called the error, will be investigated and then processed by the controller. The controller output, called the control signal, is then used to regulate the speed of the DC motor. All calculations are carried out with an Arduino Uno Microcontroller. The DC motor used in this study has specifications of 12 Vdc input voltage, 150 mA current, and a maximum speed of 7400 RPM, as shown in Fig. 3. The motor has a small current of 150 mA, so an L298N-type DC motor drive is needed, which has a maximum current of 2A.

The controller used is a Proportional Integral Derivative (PID) controller, as shown in Fig.4. The structure of the PID controller is parallel. The value of the controller output is

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_d \frac{de(t)}{dt} \tag{4}$$

where K_P, K_I, and K_D are P, I, and D parameters, respectively.

Figure 3. Motor DC

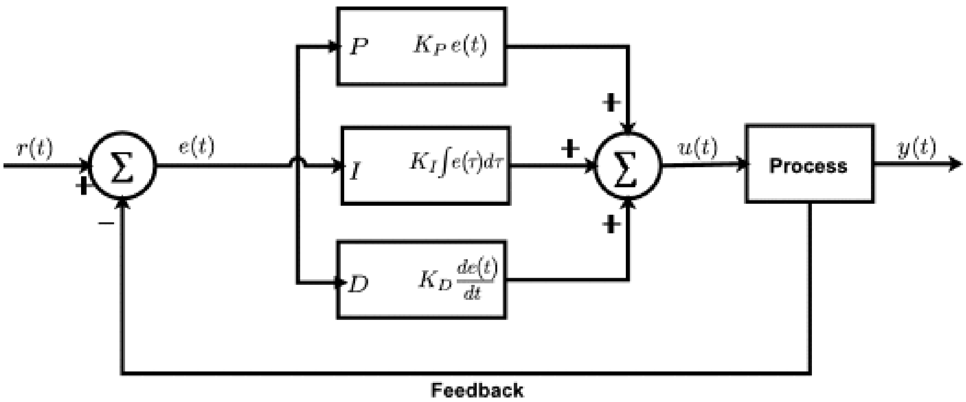


Figure 4. Block diagram of PID controller[14]

With practical experience, the heuristic approach to PID tuning is advanced, involving the human selection of controller variables based on the experimental expertise of a qualified designer who makes use of data on controlled variable estimations[14]. In the heuristic tuning procedure, there are general rules for obtaining approximate or qualitative results[12]. The first amplifier to be adjusted is K_P, starting from the lowest value until a stable response is obtained. In this first step, all K_I and K_D values are set to 0 (disabled). If a response with a steady-state error is obtained, the K_I constant is adjusted starting from a small K_I. If there is still a steady-state error, K_I is increased until the steady-state error is equal to 0. Increasing K_I usually causes a slower response. Therefore, to obtain the desired value, the differential amplifier constant can be increased starting from a small K_D, then increased until the optimum response is achieved. The system has an optimum response if it if it meets the following requirements

a. fast response

   The system produces the intended result in a short amount of time.

b. minimal overshoot

   The output stays within a reasonable range of the goal value. Overshoot is limited to 20%.

c. short settling time

   The output quickly stabilizes around the target value.

d. small steady-state error

   This means that there is little to no variation between the desired value and the final output. The SSE is limited to 2%.

e. good stability

   The system does not fluctuate or become unstable.

The flowchart of the DC motor speed sensorless control system using a PID controller is shown in Fig. 5. The flowchart includes several parts. They are initialization, reading the stator current and voltage values from the current and voltage sensors, calculating the estimated speed carried out by the observer, calculating speed calibration, calculating errors, and calculating the controller output. The moving average method is used to average the current and voltage measured by the current and voltage sensor in order to remove noise.

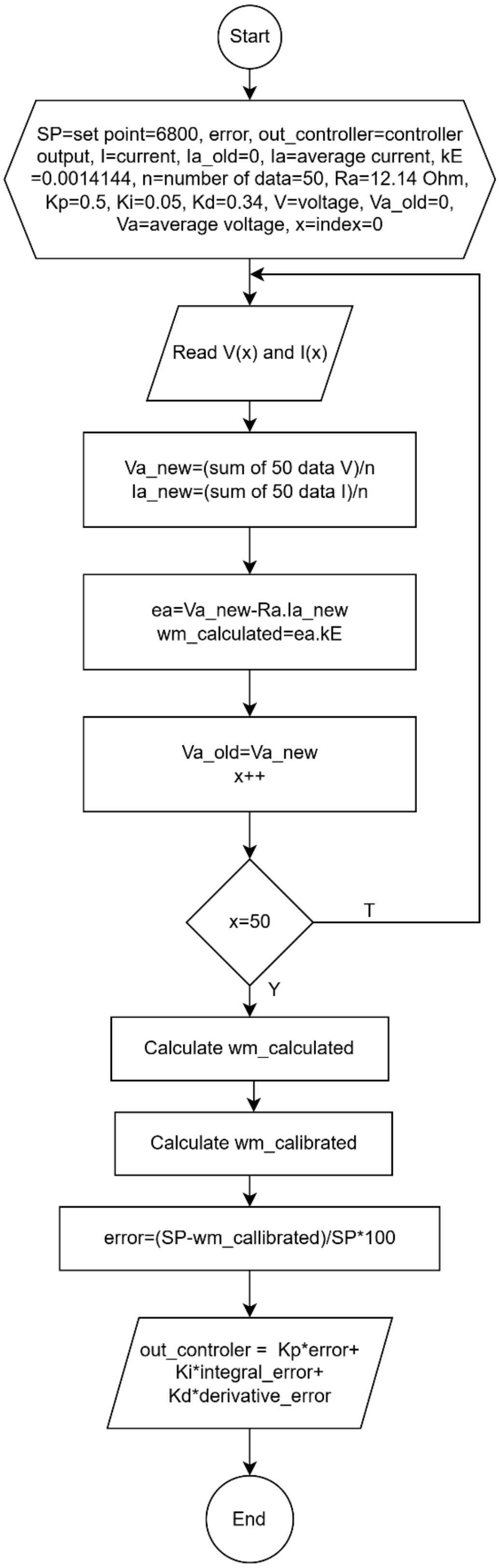


Figure 5. Flowchart of the speed sensorless control using a PID controller

3 Results and Discussions

By the methodology explained above, in this section, the research results will be explained, including the results of measuring motor parameters, observer design, and controlling the speed sensorless of a DC motor using a PID controller, including tuning controller parameters.

3.1. Result of Measuring Motor Parameters

The DC motor parameters measured are motor resistance (R_a) and motor inductance (L_a). Both parameters are measured with an LCR meter. The results of resistance measurements can be seen in Table 1, while the results of inductance measurements can be seen in Table 2.

Table 1. Motor Resistance Measurement

Position	Resistance Values (Ω)
1	12.14
2	12.14
3	12.14
4	12.14
$R_{a\_average}$	12.14

Table 2. Motor Inductance Measurement

Position	Inductance Values (mH)
1	93.20
2	93.26
3	93.25
4	93.26
$L_{a\_average}$	93.24

Resistance is measured with an RDC variable at several rotor positions, and then the results are averaged. Motor inductance is measured with an LCR meter at a frequency of 100 Hz at several rotor positions, and then the results are averaged. From the two tables, it can be seen that the DC motor used in this study has average R_a = 12.14Ω and L_a = 93.24 mH.

The R_a and L_a measurements above are then used to find the k_E value. Table 3 shows the calculation of the k_E value for the *L-R* method, while Table 4 shows the calculation of the k_E value for the *R* method. The k_E value is obtained from equation 3. The e_a value in Table 3 is obtained from equation 2, while the e_a value in Table 4 is obtained from equation 2, but the La value is ignored. The average k_E value in the *L-R* method was 0.001342, while in the *R* method it was 0.0014144.

Table 3. Calculation of k_E using the *L-R* method

v_a *(V)*	ω_m (RPM)	i_a *(mA)*	e_a	k_E
11.57	1665.0	160.5	9.6067	0.005770
11.62	7285.9	147.9	9.8264	0.001349
11.65	7285.9	174.8	9.5239	0.001307
11.65	7299.3	147.7	9.8602	0.001351
11.65	7301.8	147.4	9.8606	0.001350
			k_E average	0. 001561

Table 4. Calculation of k_E using the *R* method

$\boldsymbol{v_a}$	ω_m (RPM)	i_a *(mA)*	e_a	$\boldsymbol{k_E}$
4.88 V	2777.4	63.4	4.11	0.0014798
6.81 V	4081.1	87.5	5.75	0.0014089
11.68 V	7346.3	142.1	9.95	0.0013544
			k_E average	0.0014144

3.2. Result of Observer Design

The results of the k_E calculation are then used to calculate the estimated speed, as shown in Tables 5 and 6. When compared with the actual speed measured by the tachometer, the error will be obtained as shown in both tables. It appears that the speed error calculated using the *R* method is smaller than the *L-R* method, which is 5.38%. Therefore, the observer that will be used is the *R* method observer.

Table 5. Comparison of estimated speed and actual speed with the *L-R* observer method

i_a (mA)	v_a (V)	e_a (V)	$\omega_{m\_estimated}$ (RPM)	ω_m (RPM)	Error *(%)*
147.9	11.62	9.8264	6294.44	7285.9	13.60
147.7	11.65	9.8602	6316.1	7299.3	13.47
147.4	11.65	9.8606	6316.35	7301.8	13.49
143.7	11.66	9.9155	6351.52	7323.1	13.27
143.5	11.66	9.9179	6353.08	7317.7	13.18
143.3	11.67	9.9303	6361.03	7314.7	13.04
				Average error	13.34

Table 6. Comparison of estimated speed and actual speed with the *R* observer method

i_a (mA)	v_a (V)	e_a (V)	$\omega_{m\_estimated}$ (RPM)	ω_m (RPM)	Error *(%)*
136.2	11	9.35	6608.12	6978.9	5.31
136.3	11	9.35	6607.27	6981	5.35
137.3	11	9.33	6598.68	6973	5.37
137.32	11	9.33	6598.51	6973	5.37
138.02	11	9.32	6592.5	6973	5.46
139.52	11	9.31	6579.63	6972.8	5.64
140.4	11	9.3	6572.08	6972.8	5.75
141.82	11	9.28	6559.89	6972.8	5.92
				Average error	5.38

As shown in Table 6, although the error obtained is small, it is still above 5%. To minimize the error, calibration is necessary, as shown in Fig. 6. From the graph, it appears that the relationship between estimated speed and actual speed is linear. From the figure, it appears that the calibration equation follows equation 5.

$$y = 1.0567x + 0.7262 \tag{5}$$

where x is the estimated speed ($\omega_{m\_estimated}$) and y the calibrated speed ($\omega_{m\_calibrated}$). After calibration, the estimated speed value is close to the actual speed value with an error of 0.2019%, as shown in Table 7. The actual speed value is measured using a tachometer.

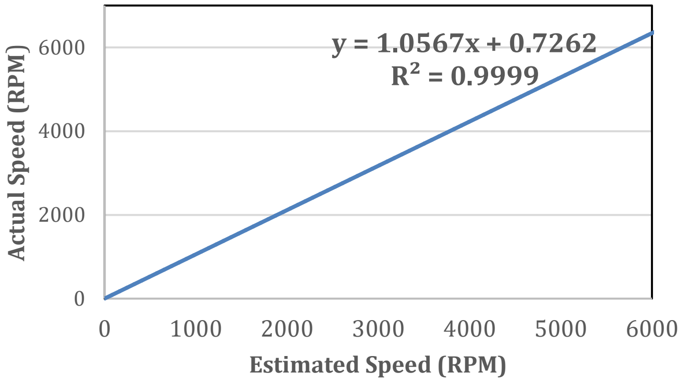


Figure 6. Calculation of calibrated speed

Table 7. The result of calibration

$\omega_{m\_calibrated}$ (RPM)	$\omega_{m\_tachometer}$ (RPM)	Error (%)
6842.59	6872.5	0.437
6852.45	6872.5	0.293
6853	6872.5	0.285
6856.63	6872.5	0.231
6857.35	6872.5	0.221
6868.48	6872.5	0.059
6870.66	6872.5	0.027
6872.11	6872.5	0.006
6872.66	6872.5	0.002
	Average error	0.2019

3.3. Result of the Speed Sensorless af a DC Motor using a PID Controller

The implementation of a sensorless speed control system to control the speed of a DC motor can be seen in Fig. 7. The system consists of a power supply, current and voltage sensors, a microcontroller, an L298N driver, and a laptop to record the measurement results. The system is also equipped with an LCD to monitor the speed. The PID controller parameter values are input through three potentiometers, which are inputs for K_P, K_I, and K_D.

Fig. 8 shows the results of tuning K_P, K_I, and K_D using the heuristic tuning method. When tuning the K_P value with a setpoint of 6800 RPM and K_P = 0.5 (Fig. 8(a)), the system response graph shows quite a high overshoot. The motor speed reaches a stable condition at 6710.74 RPM, which indicates a steady state error (SSE) of 1.3% from the setpoint. In addition, the system experiences a speed spike to 6872.8 RPM, which means an overshoot (%OS) of approximately 2.41%. This occurs because the use of proportional gain (K_P) alone causes the system to respond aggressively to errors, but without sufficient damping. As a result, the system tends to exceed the setpoint before finally stabilizing, resulting in overshoot on the response graph.

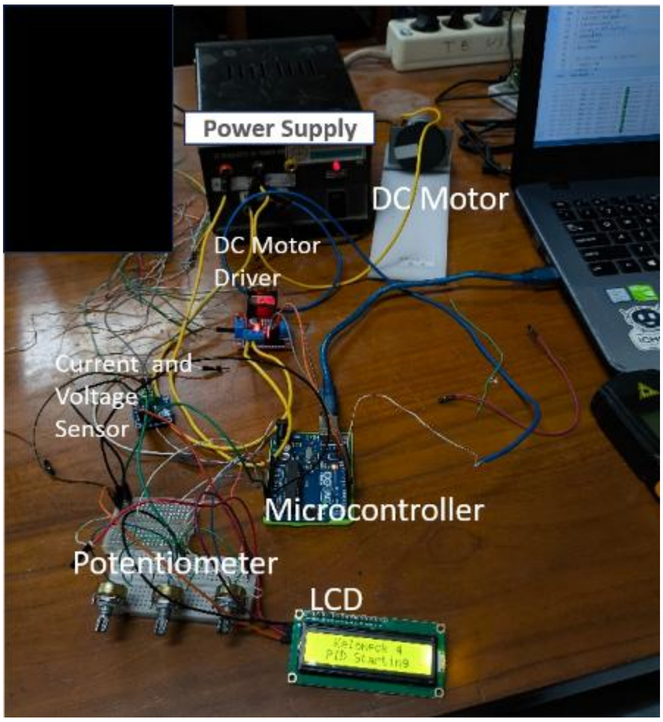
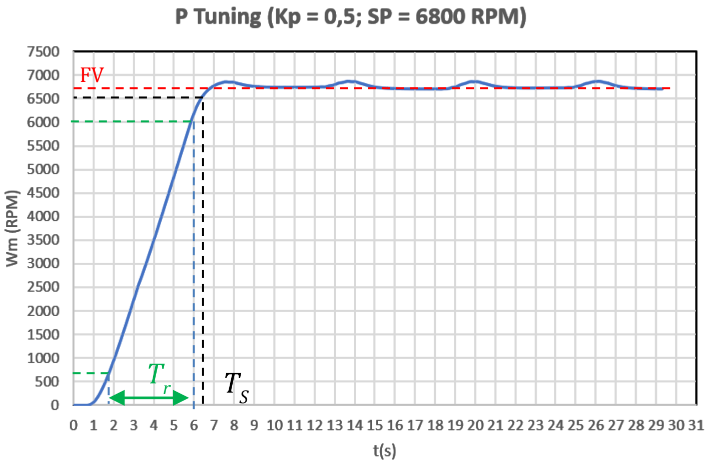
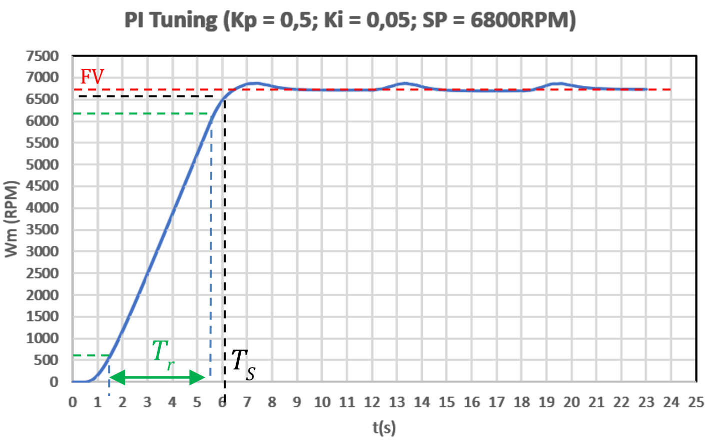


Figure 7. The implementation of a speed sensorless control system



(a)



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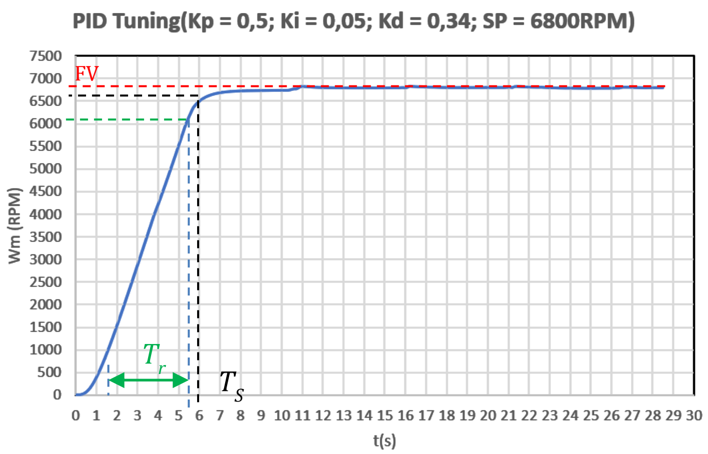

(c)

Figure 8. PID tuning using heuristic method

When tuning the Ki value with Set point = 6800RPM, K_P = 0.5, and K_I = 0.05 (Fig. 8(b)), it produces a system response graph with a slightly lower overshoot value than the K_P tuning process alone. The motor speed reaches a stable condition at 6733 RPM, which indicates a slightly smaller steady state error of 1% of the set point. However, the system experiences a speed spike up to 6874 RPM, which results in an overshoot of about 2.1% which is greater than the K_P tuning. This occurs because the addition of the integral component (K_I) makes the system more aggressive in correcting errors, including errors that accumulate over time. Without damping from the derivative component (K_D), the control action becomes excessive and tends to cause a response spike, resulting in a larger overshoot.

The last is the tuning of the K_D value with a setpoint of 6800 RPM using a combination of K_P = 0.5; K_I = 0.05; and K_D = 0.34 values (Fig. 8(c)) can provide or produce a more optimal system response graph because it produces a very small oscillation of 0.39% or can be considered no oscillation (equal to 0). The results of the system response show that the resulting DC motor speed response can reach a value of 6792.76 RPM stably and quickly approaching the set point value of 6800 RPM, with a very small level of deviation. The Steady State Error (SSE) value produced in this tuning is also the lowest, which is around 0.11%, indicating that the error between the actual value and the target speed value is at a minimum level. The system has the smallest settling time value (T_s) of the other tunings, i.e., 6 seconds. Therefore, this PID value tuning was chosen as the best configuration because it can provide stability, accuracy, and response that meet the needs of the sensorless DC motor speed control system implemented in this study. The performance results can be seen in Table 8.

Table 8. Comparison of Controller Performance

Controller	Final Value (FV)	T_r (s)	T_s (s)	%OS (%)	SSE %
P	6710.74	4.3	6.4	1.31	1.3
PI	6733.95	4	6.2	0.97	0.97
PID	6792.76	4	6	0.11	0.11

4 Conclusions

From the results of the study, it can be concluded that the R method of the DC motor speed control system with a PID controller can work well. The use of observer method 2 was chosen because it was proven to provide the most accurate speed estimation with an average error of only 0.2019%, smaller than method 1. This speed estimation is then used as feedback for the PID controller, which is tuned using the heuristic method. The PID parameter tuning results with a configuration of K_P = 0.5, K_I = 0.05, and K_D = 0.34 demonstrated optimal system performance, producing an actual speed of 6792.76 RPM from a setpoint of 6800 RPM, with a very small steady-state error (SSE) of 0.1%, a rise time (T_r) of 4 seconds, and a settling time (T_s) of 6 seconds. Therefore, the combination of observer method 2 and a PID controller proved capable of controlling DC motor speed accurately, responsively, and efficiently without relying on a physical speed sensor.

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