Comparison of Two DC Motor Speed Observers on Sensorless Speed Control Systems

Bernadeta Wuri Harini[1], Martanto[2], Tjendro[3]

***Abstract*—In a sensorless motor speed control system, the motor speed is not directly measured using a speed sensor, but it is estimated using an observer. The sensorless speed control systems are mostly applied to AC motors, while they have not been widely applied to DC motors. Therefore, this paper presents simple observers to estimate the DC motor speed. The observers used were based on the DC motor electric equation. Two methods were used in this research. The first method was the observer estimating the speed based on the resistance inductance values (L-R method), while the second was the observer estimating the motor's speed only based on the motor's resistance value (R method). The speed was estimated using armature current (i_a) and voltage (v_a). Therefore, a current and voltage sensor was used. Not only was the observer estimated, but it was also implemented on a real DC motor. An Arduino microcontroller was used to calculate the speed. The LN298 was used as a DC motor drive. Even though the R method is simpler, the test result showed that its speed estimation was less precise than the L-R method. By manual calculation, the motor speed estimation result in the L-R method had an error of 0.14%, while the motor speed estimation results in the R method had an error of 5.03%. The estimation results of motor speed implemented on a real DC motor and microcontroller system in the L-R method had an error of 3.98%, while the result of the estimation of motor speed in the R method had an error of 4.87%.**

***Keywords*—Direct Current Motor, Inductance, Observer, Resistance, Sensorless Speed Control.**

I. INTRODUCTION

Generally, there are two methods to control the motor speed, namely sensor-based control systems and sensorless control systems. The weakness of the sensor-based control compared to the sensorless one is the constraint during the installment of the sensor on the rotor as it is difficult to get a centered position. Therefore, a sensorless control system is developed to overcome this weakness [1]. In this system, the actual value of the system (controlled variable) is not measured directly using sensors. It is still estimated from the stator current and or stator voltage using an observer.

The sensorless speed control systems are mainly applied to AC motors [2]-[6] and have not been widely applied to DC motors, although they are commonly used in the control fields, such as robots [7], electric bikes [8], and solar tracking drives [9]-[10]. Therefore, sensorless control of DC motors remains understudied to get the best results. Research on a DC motor control system without a speed sensor has been previously conducted [11]-[14].

One of the important parts of sensorless control is the observer. The system must estimate the controlled variables properly so that the estimated value obtained is in accordance with the actual value. Some observers are used to estimate the motor speed. Some of these are the model reference adaptive system (MRAS) [15], Luenberger [16], extended Kalman filter (EKF) [17]-[19] and sliding mode observer (SMO) [20]-[21]. Several research has used a combination of multiple observers. For instance, they use a combination of fuzzy and SMO [22] and a combination of EKF and SMO [18], [23].

Several researchers who studied the DC motor sensorless controller used different observer and controller methods. The use of EKF observer has been studied [19]. In this paper, the controller used to control the motor was the Takagi-Sugeno-Kang fuzzy logic controller. Another research has used the reduced-order Luenberger observer [11]. The controller used was a programmable logic controller (PLC) based control. Meanwhile, the Luenberger observer with the sliding mode controller (SMC) method as the controller has been used in [12]. Another observer, such as an observer feedback vector, has been simulated [13]. The methods used in these studies required complex computations. Besides that, the four investigations in the article above have not been implemented into real motors. In another study, the estimated speed was determined by the ripple component of the motor current [14]. The number of ripple components per rotation was constant, so that the rotor speed could be estimated from this ripple component. In this method, the system must be able to detect ripples. If it is not detected, an error occurs.

In this paper, the use of observers, which are simple and easy to apply for estimating the DC motor speed, is investigated. The observers used were based on the DC motor electric equation. The electric motor equation's observer method was also proposed to estimate permanent magnet synchronous motor (PMSM) speed [24]. Additionally, the electric motor equation was used to find the real speed of PMSM because of failure in the speed estimation by the model reference adaptive system (MRAS) observer. In this condition, the MRAS observer could not estimate the real motor speed as the motor was overloaded.

Like other sensorless control methods that require motor parameter values [25]-[27], the speed estimated by the observer is also influenced by the DC motor parameter values. In this paper, two methods are used. In the first method, the observer estimates the speed based on the resistance and inductance values. In contrast, in the second method, the observer estimates the motor speed only based on the motor resistance

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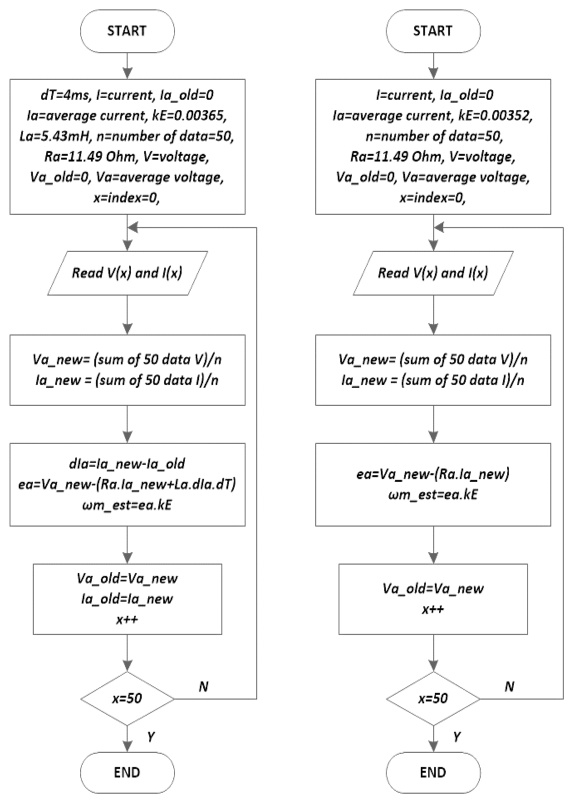
[Received: 7 July 2022, Revised: 1 August 2022]



(a) (b)

Fig. 1 Methods of DC motor observer, (a) L-R method and (b) R method.

value. Therefore, the first method is called the L-R method, and the second is called the R method.

II. METHODOLOGY

The sensorless control system in this research was used to control one DC motor. The specification of the DC motor is a 24 V voltage supply, 2 A full load current, and 6,000 rpm speed. The introduction section has explained that the sensorless control system requires motor parameter values. The DC motor parameters required are armature resistance (R_a) and armature inductance (L_a). Both of these parameters were measured using an LCR meter.

The research procedures comprise several steps. First, the DC motor's R_a and L_a was measured using an LCR meter. They were measured at several positions. Then, several results of measurements were calculated to get the average value which was then used for the following calculation. Second, the value of the back emf constant (k_E) was calculated using two methods. These methods used equations based on the DC motor circuit which will be explained later. From several calculations of k_E, the average k_E value was sought. This average k_E value was used to calculate the estimation speed. After getting the k_E value, the estimation speed was calculated using two methods which will explained later. The estimation speed calculation was then implemented on a real DC motor. A microcontroller system was used to calculate the estimation speed. Both method results were then analyzed and compared to get the best method of the DC motor speed observer.

The flowcharts for both methods are shown in Fig. 1. The first method of the DC motor observer is shown in Fig. 1(a), while the R method of the DC motor observer is shown in Fig. 1(b).

The armature current (i_a) and voltage measured directly using the current and voltage sensor had a problem, i.e., the occurrence of noise. To eliminate this noise, the current and voltage measured using the current and voltage sensor were averaged using the moving average method, as shown in Fig. 1. This moving average method was applied both ways.

The algorithm of the moving average is:

1. Initialization of motor parameters. It depends on the method used, whether the L-R or R method, which will be explained later.
2. Initialization of averaged data length $n = 50$.
3. Prepare the voltage data storage memory with the 1st index to the nth index and fill all voltage storage with a value of 0 V.
4. Prepare the current data storage memory with the 1st index to the nth index, and fill the current storage with 0 A.
5. Initialization of x to 1.
6. Initialization of $V_{a\_old} = 0$ and $I_{a\_old} = 0$.
7. Make the loop as follows.
   a. Take the voltage from the voltage sensor and store it in the xth voltage data as $V[x]$.
   b. Take current from the current sensor and store in the xth current data as $I(x)$.
   c. Find the sum value of 50 voltage data, and save it as sum_v.
   d. Calculate the mean storage voltage as V_{a_new} = sum_v / 50.
   e. Find the value of the sum of 50 current data stored as sum_i.
   f. Calculate the mean current store as I_{a_new} = sum_i / 50.
   g. Calculate the other parameters depends on the method to be used, whether the first or R method that will be explained later
   h. Calculate $V_{a\_old} = V_{a\_new}$ and $I_{a\_old} = I_{a\_new}$.
   i. Increment the x value. If $x > 50$, then x is set to 1.
   j. Continue to step 7.a.

The data length $n = 50$ was determined by the experiment, that was when the data noise was removed. The experiment showed that the moving average of one cycle was 4 ms. As a result, the sampling time (dt) was set to 4 ms. This sampling time was used for the L-R method.

A. L-R Method

The equivalent circuit of the DC motor is shown in Fig. 2 [14]. The analogous circuit illustrates the transformation of electrical and mechanical power. The i_a is flowing in this illustration. The mechanical load must rotate at the angular velocity of ω_m to be rotated by the electromagnetic torque T_{em} created by this current. When the armature rotates at ω_m rpm, a voltage known as the back electromotive force (emf) or counter emf (e_a) is induced across the armature terminals. On

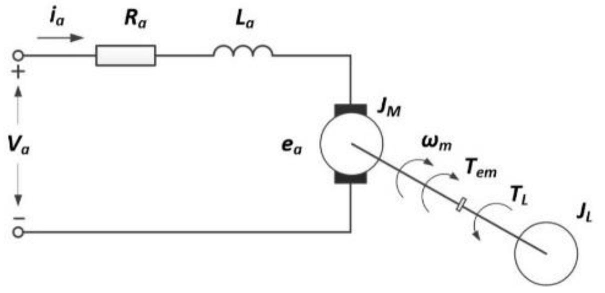


Fig. 2 Equivalent circuit of a DC motor.

the electrical side, the current flows when the e_a less than the armature voltage (v_a).

With the aid of Kirchhoff's voltage law, (1) may be used to represent the electrical side of the DC motor as current flows over the armature winding resistance and inductance.

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \quad (1)$$

where v_a is the armature supply voltage, i_a is the armature current, R_a is the armature resistance, L_a is the armature self-inductance caused by armature flux, and e_a is back-emf.

Using (1), the value of e_a can be obtained by measuring the value of the R_a and L_a of the motor, as well as the value of the v_a and i_a, so that the e_a value is obtained using (2).

$$e_a = v_a - \left(R_a i_a + L_a \frac{di_a}{dt}\right). \quad (2)$$

The e_a is proportional to the angular speed of the rotor and can be calculated using (3).

$$e_a = k_E \omega_m \quad (3)$$

where k_E denotes the back emf constant and ω_m denotes the motor speed. With the value of e_a calculated using (2) and the value of k_E obtained from the experiment, the motor speed at any time can be calculated using (4).

$$\omega_m = \frac{e_a}{k_E}. \quad (4)$$

Based on (2)-(4), a flowchart of the DC motor speed observer for the L-R method can be arranged as shown in Fig. 1(a). The parameters inputted in the program for the L-R method were R_a, L_a, k_E, and time sampling (dt). In this L-R method, the current differences were calculated every time, as shown in (2).

The resistance and inductance values stated in the flowchart were manually obtained from measurements using an LCR meter. Then, the value of k_E was determined using the following procedures.

1. Giving a specific motor input voltage.
2. Measuring the v_a using a voltmeter, the i_a using an ammeter, and the motor speed using a tachometer. The measurement is starting from when the power supply is turned on until the speed is stable for a specific motor input voltage.
3. Calculating e_a using (2).
4. Calculating k_E using (5) for each time t.

$$k_E = \frac{e_a}{\omega_m} \quad (5)$$

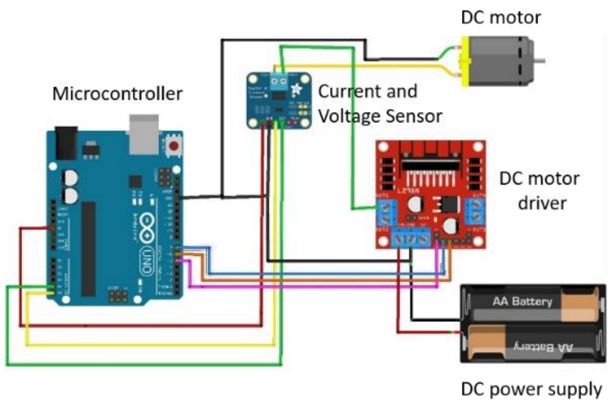


Fig. 3 DC motor observer circuit.

5. Calculating the average of k_E.

B. R Method

Observer DC motor using R method is a simplification of the L-R method, where the speed of the DC motor does not take into account the value of the motor inductance. It is possible to disregard the inductance since the mechanical time constants are significantly greater than the electrical time constants [28]. The voltage applied to the armature (v_a) is equal to the sum of voltage at resistance and the e_a. Therefore, the e_a equation uses (6).

$$e_a = v_a - i_a R_a. \quad (6)$$

The flowchart of the DC motor speed observer using the R method is shown in Fig. 1(b). In this R method, the calculation of differences in current at any time is not required, as shown in (6). Therefore, the R method's parameters inputted in the program were R_a and k_E.

As in the L-R method, the i_a and voltage measured using the current and voltage sensor were averaged using the moving average method to eliminate the noise. This process is shown in the flowchart in Fig. 1(b).

As in the L-R method, the resistance and inductance values stated in the flowchart are obtained from measurements using an LCR meter. The value of k_E was determined using the following procedures.

1. Giving the motor voltage starting from a small voltage.
2. Turning on the power.
3. Waiting until the motor is stable.
4. Measuring the v_a using a voltmeter, the i_a using an ammeter, and the motor speed using a tachometer when the motor speed is stable.
5. Calculating e_a using (6).
6. Calculating k_E using (5).
7. Repeating processes 1-6 for several greater voltages.

The two observer methods above were then implemented on a DC motor. To calculate the speed estimation, a microcontroller system was used. The circuit of the observer used is shown in Fig. 3. As seen in Fig. 3, the microcontroller system consists of several part: (a) an Arduino Uno microcontroller, (b) an INA219 current and voltage sensor, (c) an L298N DC motor driver, and (d) a battery or DC power supply.

TABLE I
RESISTANCE AND INDUCTANCE MEASUREMENT

No.	R_a (Ω)	L_a (mH)
1	10.60	5.22
2	10.84	5.47
3	11.90	5.54
4	12.65	5.49
Average	11.49	5.43

TABLE II
CALCULATION OF K_E USING THE L-R METHOD

t (s)	v_a (V)	ω_m (rpm)	i_a (A)	e_a (V)	k_E
5	20.2	4,923.80	0.198	17.92	0.00364
15	20.2	4,948.30	0.189	18.03	0.00364
30	20.22	5,002.30	0.170	18.27	0.00365
45	20.22	5,034.80	0.159	18.39	0.00365
60	20.22	5,038.20	0.158	18.40	0.00365
Average					0.00365

The Arduino Uno microcontroller was used to calculate the motor speed. The INA219 current and voltage sensor measured stator current and voltage. The current and voltage are used for estimating the motor speed. The DC power supply used in this research is variable.

The result of the implementation on a DC motor and a microcontroller system was compared with the result of speed observer calculation manually. In this context, “manually” means that after measuring the i_a with an ammeter and the v_a with a voltmeter, the estimation speed is calculated. The estimation speed was then compared to the actual motor speed using a tachometer.

III. RESULTS AND DISCUSSION

Both methods described in the methodology were tested and analyzed. Before testing both observers, the DC motor parameters, i.e., motors’ resistance and inductance, were measured.

A. Parameters Measurement

The results of the R_a and L_a measurements with the LCR meter are shown in Table I. The parameters R and L were measured in four positions with each position had a R_a and L_a value. Therefore, the values of a R_a and L_a were varied. The variation of R_a values ranged from 10.60 Ω to 12.65 Ω, while the variation of L_a values ranged from 5.22 mH up to 5.54 mH. Based on the four measurements, the average R_a value was 11.49 Ω, while the average L_a value was 5.43 mH. The average values of R and L were then inputted into the program, as shown in the flowchart in Fig. 1(a). The flowchart in Fig. 1(b) only inputted the average R value.

The manual calculation of k_E value for the L-R method for every 5 s is shown in Table II. The input voltage given was 20.22 V. The v_a was measured using a voltmeter, and the i_a was measured using an ammeter. The speed (ω_m) was measured using a tachometer.

As motors’ R_a and L_a values had been obtained, i.e., R_a = 11.49 Ω and L_a = 5.43 mH, the e_a value was calculated using (2); meanwhile, the k_E value was calculated using (5). For example, the calculation of e_a value based on (2) is shown in (7).

$$e_a = 20.2 - \left(11.49 * 0.189 + 0.00543 * \frac{0.189-0.198}{10}\right) \quad (7)$$
$$= 18.03 \text{ V}.$$

The calculation above is the calculation of e_a for t = 15s. The di_a was calculated from the differences between i_a at t = 15 s and at t = 5 s. The other calculations were done the same way as this calculation. The calculation of t = 5 s at di_a was calculated from the differences between the i_a at t = 55 s and at t = 0 s.

The example of the k_E value calculation based on (5) is shown in (8). This calculation is for t = 15s. The other calculations were carried out in the same manner.

$$k_E = \frac{e_a}{\omega_m} = \frac{18.03}{4948.3} = 0.00364. \quad (8)$$

Subsequently, from several k_E calculations, an average k_E value of 0.00365 could be obtained. This value was inputted into the program, as shown in the flowchart in Fig. 1(a).

TABLE III
CALCULATION OF K_E USING THE R METHOD

v_a (V)	ω_m (rpm)	i_a (A)	e_a (V)	k_E
5	1,140.8	0.13	3.506	0.00307
10	2,336.9	0.135	8.449	0.00362
15	3,652.5	0.151	13.265	0.00363
20	5,007.6	0.162	18.139	0.00362
25	6,315.1	0.178	22.955	0.00363
Average				0.00352

Table III shows the calculation of the k_E values for the R method for five values of input voltage (v_a), namely 5 V, 10 V, 15 V, 20 V, and 25 V. For each input voltage, the i_a and the speed (ω_m) were measured when the speed was stable; it differs from the L-R method. In the L-R method, the motor was given one value of voltage. Then, the speed, voltage, and current are measured starting when the power is on until the speed is stable.

The e_a value is calculated using (6) with the previous R_a motor values. In this method, the motor armature inductance value is not used. The k_E value is then calculated using (5). For example, calculating the e_a value based on (6) is shown in (9). This calculation is for v_a = 5 V. The other calculations are the same procedure as this calculation.

In the L-R method, the motor was given one voltage value. Then, the speed, voltage, and current were measured from when the power was on until the speed was stable.

$$e_a = v_a - i_a R_a = 5 - 0.13 * 11.49 = 3.506 \text{ V}. \quad (9)$$

The example of the k_E value calculation based on (5) is shown in (10). This calculation is for v_a = 5 V. The other calculations were done the same way as this calculation.

$$k_E = \frac{e_a}{\omega_m} = \frac{3.506}{1140.8} = 0.00307. \quad (10)$$

Next, Table III displays that the average k_E of 0.00352 was obtained. This value was then inputted into the program, as shown in the flowchart in Fig. 1(b).

(a) (b)

Fig. 4 Methods of observer testing, (a) manual and (b) using a microcontroller system.

TABLE IV
MANUAL CALCULATION OF THE L-R METHOD OBSERVER

No	ω_m (rpm)	$\omega_{m\_calculated}$ (rpm)	Error (%)
1	4,923.8	4,913.00	0.22
2	4,948.3	4,941.42	0.14
3	5,002.3	5,006.90	0.09
4	5,034.8	5,041.63	0.14
5	5,038.2	5,044.79	0.13
Average			0.14

B. Observers Testing Results

The observers were tested using two methods, i.e., manually and using a microcontroller system, as shown in Fig. 4. The manual method is shown in Fig. 4(a). As explained in the methodology section, in this method, the v_a was measured using a voltmeter, the i_a was measured using an ammeter, and the speed was measured using a tachometer. Fig. 4(b) shows the observer testing using a microcontroller system. The DC motor observer circuit is shown in Fig. 3. Both observers were tested using both testing methods. In this section, manual testing and using the program, namely the microcontroller system, were analyzed and compared to find out whether the two testing methods have the same results or have the same tendency.

1) L-R Method: Table IV shows the manual calculation of the L-R method observer. In this table, the motor speed calculated ($\omega_{m\_calculated}$) using (2) and (4) was compared to the speed measured using a tachometer ($\omega_{m\_measured}$). The motor speed estimation result in the L-R method had an error of 0.14%, as seen in Table IV. Manual motor speed calculation using the L-R method performed well even with an error of << 5%. An error of << 5% suggests that manual calculation of motor speed using the L-R method has a good performance and is suitable for estimating the motor speed. The L-R method has a good performance since the calculated speed difference from the actual speed is not too large.

The comparison between calculated speed using the $\omega_{m\_calculated}$ and $\omega_{m\_measured}$ using a tachometer at the L-R method is shown in Fig. 5. It can be seen that both values had almost the same value; for example, the speed at PWM values of 135, 190, and 235. Most of the measured speed was higher than the calculated speed, except for the PWM value of 255. At this PWM value, the measured speed was lower than the calculated speed. The result of the motor speed estimation implemented on a real DC motor using an Arduino Uno microcontroller in the L-R method had an average error of

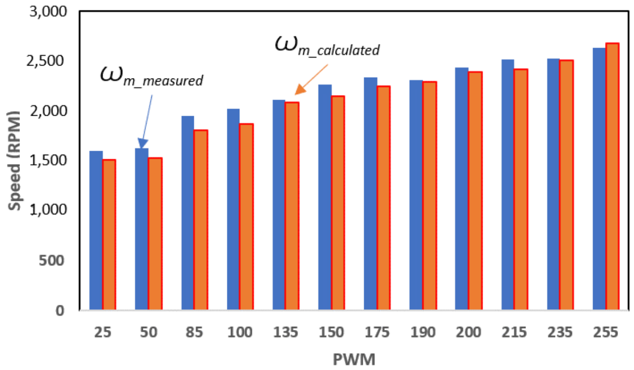


Fig. 5 L-R observer method testing using a microcontroller system.

TABLE V
MANUAL CALCULATION OF R METHOD OBSERVER

No.	ω_m (rpm)	$\omega_{m\_calculated}$ (rpm)	Error (%)
1.	1,140.8	997.24	12.58
2.	2,336.9	2,403.26	2.84
3.	3,652.5	3,773.30	3.31
4.	5,007.6	5,159.70	3.04
5.	6,315.1	6,529.75	3.40
Average			5.03

3.98%. The L-R method for estimating the motor speed still performed well even with an error of < 5%. It indicates that the L-R method is also suitable for estimating motor speed.

2) R method: The R method is simpler than the L-R method. Based on (6), it can be seen that the motor inductance value and the calculation of i_a differences are not required every time. The manual calculation of motor speed using the *R* method observer is shown in Table V. If compared with the motor speed measured using a tachometer, it can be seen that the motor speed estimation results in the R method had an average error of 5.03%. The higher estimation result of more than 5% suggests that the second motor speed estimation method produces less precise results than the first motor speed estimation method. The highest error occurred when the motor ran at a low speed, which in Table V is shown when the motor runs at 1,140.8 rpm; the error was 12.58%, which was far from the actual speed. This method is suitable for estimating the motor speed at higher speeds as the error will be below 4%.

The comparison between calculated speed using the microcontroller system ($\omega_{m\_calculated}$) and measured speed using a tachometer ($\omega_{m\_measured}$) in the R method is shown in Fig. 6. Most of the measured speed was higher than the calculated speed, likewise the L-R method result. Even so, the differences were greater than that of the L-R method. The high differences occurred at PWM values of 25, 50, 135, 150, and 175. The other PWM values had fewer differences, such as the speed at PWM values of 190 - 255. The result of the estimation of motor speed implemented on a real DC motor using an Arduino Uno microcontroller system in the R method had an average error of 4.87%. Even though the error was under 5%, it was higher than the error percentage of the L-R method.

According to the preceding discussion, the R method's speed estimation is less precise than the L-R method, both manually

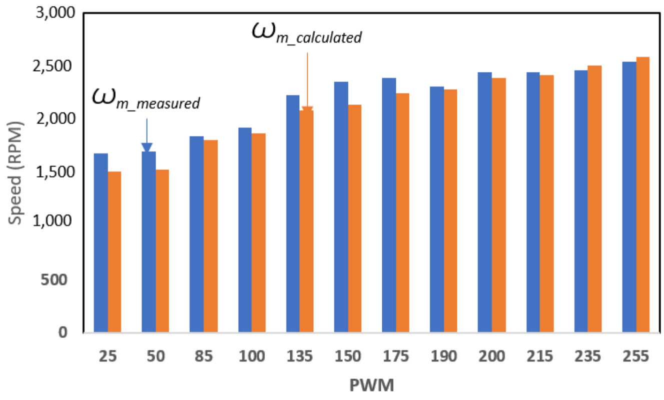


Fig. 6 Second observer method testing using a microcontroller system.

and using a microcontroller system. Therefore, it is better to use the L-R method. The R method's advantage is that it is simpler than the L-R method. It does not need to measure the DC motor's L_a at several positions. With an error percentage below 5%, the R method was still used to estimate the DC motor speed, although the average error was greater than the L-R method. If the R method is used to estimate the motor speed, a program addition is required to adjust the speed. It is possible to accomplish this with a microcontroller and equation addition. For example, using a linear equation, the DC motor speed can be adjusted using (11). The error percentage at this condition is 1.84%.

$$\omega_{m\_adjusted} = 0.9\omega_{m\_calculated} + 282.61. \qquad (11)$$

IV. Conclusion

The R method is simpler, but the speed estimation is less precise than the L-R method. By manual calculation, the motor speed estimation results in the L-R method had an error of 0.14%, while the motor speed estimation results in the R method had an error of 5.03%. The estimation of motor speed implemented on a real DC motor in the L-R method had an error of 3.98%, while the result of the estimate of motor speed in the R method had an error of 4.87%.

Conflict of Interest

The authors whose names are listed in the article titled "Comparison of Two DC Motor Speed Observers on Sensorless Speed Control Systems" state that there is no conflict of interest.

Author Contribution

Conceptualization, Bernadeta Wuri Harini; research methodology, Tjendro; software, Martanto; validation, Tjendro; formal analysis, Bernadeta Wuri Harini; source, Martanto; writing—Bernadeta Wuri Harini.

Acknowledgment

The authors gratefully acknowledge the LPPM of Universitas Sanata Dharma for supporting this research.

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