BLDC Motor Stability Management Using Adaptive PID (MRAC-PID)

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Article Information:

Received:
25 September 2023

Received in revised form:
29 october 2023

Accepted:
10 November 2023

Volume 5, Issue 2, December 2023
pp. 98-104

http://doi.org/10.23960/jesr.v5i2

Abstract

BLDC motors have become popular in various industries such as automotive, consumer, healthcare, industrial automation, and instrumentation due to their optimal performance. To keep the BLDC motor in optimal condition, a control engineering system is required that serves as a controller. A single Proportional Integral Derivative (PID) control system is only suitable for linear conditions, so it cannot produce satisfactory output when there is a change in set point. To overcome this obstacle, an adaptive PID control system known as MRAC-PID control system is applied, which is able to control the stability of the BLDC motor as desired. Testing of this system is done under 4 different conditions using MATLAB software. After testing, the parameter values for the MRAC control system were obtained, namely Kp = 0.4; Ki = 50.75; Kd = 0.0000867. Based on the test, the MRAC control system produces a system success rate of 81.2% to 98.9%.

Keywords: *BLDC motor, MRAC-PID.*

I. Introduction

Currently, technology is developing very rapidly in various fields of life such as industry, information, transportation and other fields. One example of the development of technology that exists today is the development of electric motors. An electric motor is a device that can convert electrical energy into mechanical energy [1]. One of the electric motors that is widely used today is the Brushless DC (BLDC) Motor. BLDC motors have been widely used in industries such as the automotive, consumer, health, industrial automation, and instrumentation industries and have advantages such as high inertia/torque ratio high efficiency, large speed regulation range, and low electromagnetic interference (EMI) [1].

Although it has many advantages, BLDC motors also have several disadvantages, including the lack of stability of the motor speed when given a load in such a way, that it causes the BLDC motor speed to be less stable. Considering that BLDC motors have been widely applied in various industrial and automotive fields, the performance of these motors must be optimal. To ensure that the BLDC motor remains in an optimal state, a control engineering system is needed as a system controller.

Control systems have been widely applied to electronic equipment, including BLDC motors. One of the control systems that has been applied is a motor speed control system with a single Proportional Integral Derivative (PID) control. This control system is only able to work for linear conditions. So that This single PID control system has not been able to produce good enough output when given such loading [2].

Based on the above problems, a study was conducted to design a PID control system to control the stability of an adaptive BLDC motor that can produce the output of BLDC motor stability as expected under load or no load.

A. BLDC Motor

The working principle of this BLDC motor uses the electromagnetic principle, the force of attraction between permanent magnets on the rotor and electromagnets on the stator. To make the BLDC motor rotate or move, the stator winding must be energized sequentially. When the magnetic poles of the rotor are near the Hall sensor, it will give a high or low signal, indicating the N or S poles are passing near the sensor. Based on the combination of these three Hall sensor signals, the exact switching sequence can be determined [1].

When the motor rotates, the permanent magnets in the rotor will move past the coil in the stator which will then induce an electric potential in the coil and there is a BEMF or Back electromotive force. This BEMF is directly proportional to the motor speed [3].
The rotational speed of the motor can be seen through the following equation:

$$\omega = \frac{Vt - IaRa}{K\emptyset} \quad (1.1)$$

Where:

ω = motor rational speed (rad/sec)

Vt = motor input voltage (V)

Ia = motor input current (A)

Ra = motor armature resistance (Ohm)

$K\emptyset$ = magnetic flux constant

The torque produced in a BLDC motor depends on the amount of current and the number of turns in the stator, the magnetic field strength of the permanent magnets in the rotor, the air gap between the stator and rotor, and the length of the permanent magnets in the rotor [4]. The amount of torque value produced can be seen in the following equation:

$$\tau = K\emptyset \, . Ia \quad (1.2)$$

Thus, the transfer function can be found by using the ratio of the angular velocity ω_m to the voltage source V_s

$$G(s) = \frac{\omega_m}{V_s} = \frac{k_t}{s^2J + sk_f + sRJ + k_fR + K_ek_t} \quad (1.3)$$

$$G(s) = \frac{\omega_m}{V_s} = \frac{k_t}{s^2J + (RJ + k_fL) + k_fR + K_ek_t} \quad (1.4)$$

Considering the following assumptions:

1. Constant friction is small k_f close to 0, which means that
2. $RJ \gg k_fL$ dan
3. $k_ek_t \gg Rk_f$

$$G(s) = \frac{\omega_m}{V_s} = \frac{k_t}{s^2JL + RJs + k_ek_t} \quad (1.5)$$

$$G(s) = \frac{\omega_m}{V_s} = \frac{\frac{k_tR}{k_ek_tR}}{\frac{s^2JLR}{k_ek_tR} + \frac{RJSR}{k_ek_tR} + \frac{k_ek_tR}{k_ek_tR}} \quad (1.6)$$

$$G(s) = \frac{\frac{1}{k_e}}{\frac{RJ}{k_ek_t}.\frac{L}{R}s^2 + \frac{RJ}{k_ek_t}s + 1} \quad (1.7)$$

Based on equation (1.7) above, the formula is obtained:

for mechanical (time constant):

$$\tau_m = \frac{RJ}{k_ek_t} \quad (1.8)$$

for electrical (time constant):

$$\tau_e = \frac{L}{R} \quad (1.9)$$

Then, substitute the values of τ_m and τ_e into equation (1.7), thus obtaining

$$G(s) = \frac{\frac{1}{k_e}}{\tau_m.\tau_e \, .s^2 + \tau_m \, . \, s + 1} \quad (1.10)$$

B. Model Reference Adaptive Controller (MRAC)

A PID control system is a system composed of three control elements: proportional, integral, and derivative. The three elements can be combined into several types of control systems according to the required plant. These elements have different effects on the controlled system.

An adaptive control system is a control system that can adapt to the conditions of the controlled system, both from outside the system and from within the system itself. Model Reference Adaptive Controller (MRAC) is one of the adaptive schemes where the output performance of the system (process) follows the output performance of the reference model.

The controller parameters are set through a setting mechanism based on the error, which is the difference between the plant output and the reference model output [5].

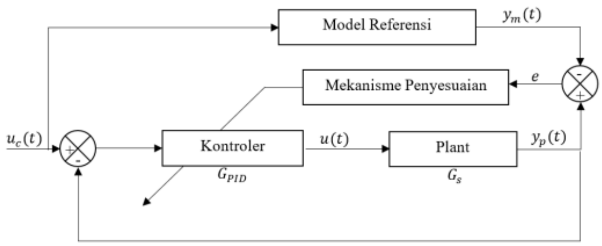

Figure 1. Block diagram of MRAC

From the block diagram above, it can be seen that there are 2 loops, the first loop is the normal feedback loop between the process output and the controller and the second loop is the loop used by the controller setting mechanism. In this second loop, the process is carried out to update controller parameters and plant parameters according to the adaptive scheme used. The setting is done by minimizing the error signal so that the system output (y) matches the reference model output (y_m) [5].

In this study, the determination of the MRAC mathematical model can be determined using second-order characteristics by following the following reference model equation:

$$y_m(s) = \frac{\omega_n^2}{s^2+2\beth\omega_n s+\omega_n^2} \quad (1.11)$$

Where :

$$\omega_n = \frac{4}{\beth t_s} \quad (1.12)$$

$$t_s = \frac{4}{\beth \omega_n} \quad (2.48)$$

The magnitude of $\beth$ can affect the response of the reference model. If $\beth < 1$ will underdamp the response, if $\beth = 1$ will critical damp, and if $\beth > 1$ will overdamp the response.

II. Materials and Methods

The type of research conducted is system simulation. System simulation is carried out by providing loading to the BLDC motor plant. Data collection in this simulation will be carried out by providing conditions without load and also with load. Furthermore, each of these will be seen in the system response graph in MATLAB Simulink. The BLDC motor used is the Maxon EC flat Ø 45 mm type with the following characteristics.

Tabel 1. Characteristics of BLDC Motors

Parameter of BLDC Motor	**value**	units
Nominal voltage value		
Nominal Voltage	12.0	V
No load Current	150	mA
Nominal Speed	2850	Rpm
No load Speed	4371	Rpm
Nominal Torque	59.1	mNm
Nominal Current	2.13	A
Stall Torque	255	mNm
Starting Current	10.0	A
Maximum Efficiency	77	%
Characteristics		
Terminal resistance phase to phase (R)	1.1	Ω
Terminal inductance phase to phase (L)	0.50	mH
Constant rotation (k_t)	25.5	mNm/A
Constant speed (k_e)	35.4	Rpm/V
Speed/rotation gradient (k_0)	17.6	Rpm/Nm
Mechanical time constant (k_m)	16.2	mS
Rotor Inertia (J)	82.5	gcm^2
Number of phasa	3	

A. *Mathematical Modeling of BLDC Motor*

BLDC motors have 2 types of motion produced, namely mechanical constant and electrical constant. then the mathematical equations for mechanical time and electrical time in BLDC motors can be written as follows.

Mechanical time constant:

$$\tau_m = 0{,}0162\ sekon$$

$$k_e = \frac{(82.5\times10^{-6})(3)(1.1)}{(0.0162)(25.5\times10^{-3})}$$

$$k_e = 0{,}0659$$

Electrical time constant:

$$\tau_e = \frac{0.5\times10^{-3}}{(3)(1.1)}$$

$$\tau_e = 0{,}000151\ sekon$$

Then the equation for the BLDC motor can be obtained by calculating the constant and phase effects. BLDC motor modeling in the form of a transfer function can be written as follows.

$$\frac{1}{k_e} = \frac{1}{0.0659} = 15{,}17$$

$$\tau_m.\tau_e = (0{,}0162)(0{,}000151)$$

$$= 2{,}45 \times 10^{-6}$$

In accordance with the transfer function equation (1.10), the BLDC motor transfer function becomes

$$G(s) = \frac{15.17}{(2.45\times10^{-6})s^2+(0.0162)s+1}$$

B. *Controllability Testing*

Controllability testing is one step to find out whether the object or plant can be controlled or not, this test is carried out before designing the control system. A system can be controlled if the matrix determinant value is not equal to zero ($det[B|AB|A^2B] \neq 0$).

From the BLDC motor transfer function G(s) that has been obtained, the matrices A, B, C, and D of the function can be determined. The matrices A, B, C, and D of the BLDC motor transfer function are obtained:

$$A = \begin{vmatrix} -6610 & -408160 \\ 1 & 0 \end{vmatrix}$$

$$B = \begin{vmatrix} 1 \\ 0 \end{vmatrix}$$

$$C = |0 \quad 6.2 \times 10^6|$$

$$D = |0|$$

The calculation of the value ($det[B|AB|A^2B] \neq 0$) uses a listing program in MATLAB common windows:

```
%Controllability

num = [15.17];
den = [0.00000245 0.0162 1];
[A,B,C,D]=tf2ss(num,den)
sys=ss(A,B,C,D)
Co=ctrb(sys)
rank(Co)
```

The value of $[B|AB|A^2B]$ direpresentasikan dengan nilai Co, is represented by the value of Co, and the value of $det([B|AB|A^2B])$ is represented by the value of *rank(Co)*.

$$Co = \begin{bmatrix} 1 & -66122 \\ 0 & 1 \end{bmatrix}$$
$$rank(Co) = 2$$

In this controllability test, if the result of rank (Co) is not equal to 2 ($\neq 2$) then the system cannot be controlled, and if the result is equal to 2 ($= 2$) then the system can be controlled. In determining the reference model in the BLDC motor system using the MIT rule method.

C. BLDC Motor Open Loop Simulation

Open loop system simulation is done to find out the response characteristics of the BLDC motor system before being given a controller. Simulation is done by giving a step input signal to the BLDC motor system without any feedback signal. The open loop simulation circuit can be seen in Fig.2.

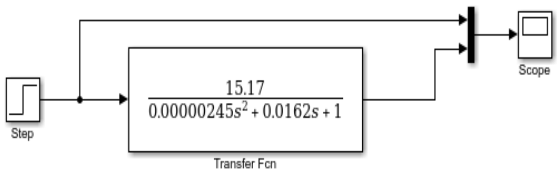

Figure 2. Open-loop circuit.

In this simulation, input is given in the form of a unit step with a set point input value of 1V, a step time of 0.5 seconds, and a sample time of 0.05 seconds.

Based on the simulation carried out, the system response graph is obtained as in Fig. 3.

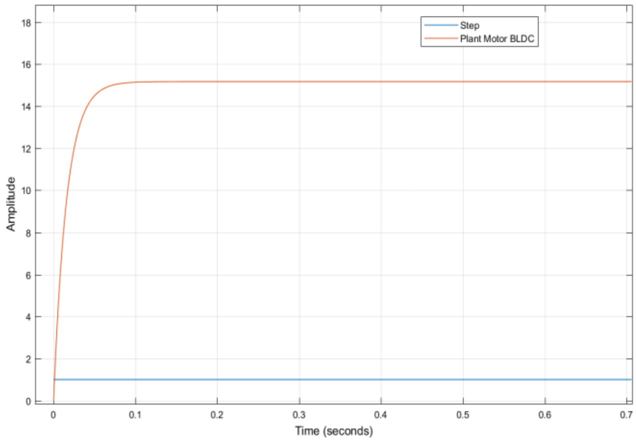

Figure 3. Open-loop system response.

The system response graph results in a settling time (t_s) value of 0.05 seconds.

D. MRAC control system design

To design an MRAC control system, the first thing to do is to determine or create a reference model that will be used in controlling the system. The damping value (ב) is determined to be 1, namely the critical damp state. The damping value in the critical damp state will provide a system condition that returns to stability after being given a disturbance so that the system response is faster in reaching equilibrium after being given a disturbance. Based on equation (1.12) the angular velocity of the BLDC motor is:

$$\omega_n = \frac{4}{(0{,}05 \times 1)} = 80\ rad/s$$

The MRAC reference model can be written as follows.

$$y_m = \frac{(80)^2}{s^2+2(80)(1)s+80^2}$$

$$y_m = \frac{6400}{s^2+160s+6400}$$

With the error value (e):

$$e = y_{plant} - y_m$$

E. Determining Response Characteristics

In designing a control system, first, determine what kind of response is desired. In this research, the desired response is simulated through the PID tuner tool. The desired response equation refers to the BLDC motor transfer function equation obtained from the mathematical modeling of the BLDC motor (G(s)).

The results of automatic tuning using a PID tuner are as follows.

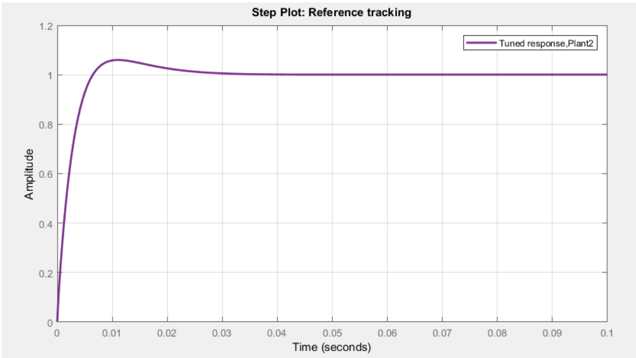

Figure 4. PID tuner tuning result.

Based on the tuning results, the parameter $Kp = 0{,}4199$ $Ki = 50{,}7294$ and $Kd = 8{,}67 \times 10^{-5}$ and has a rise time value of 0.00439 seconds, settling time value of 0.218 seconds, overshoot of 5,97% and peak value of 1.06.

The results obtained using the PID tuner are then used as reference material in determining the response generated in the MRAC simulation.

III. Results and Discussions

In this research, the simulation of the MRAC control system is done with 2 different conditions. The first condition is the simulation of the system in normal conditions, the second condition is by giving a load in the form of a portable fan. Testing the response of the MRAC control system is done using MATLAB Simulink.

The simulation circuit used in this study is shown in Fig. 5.

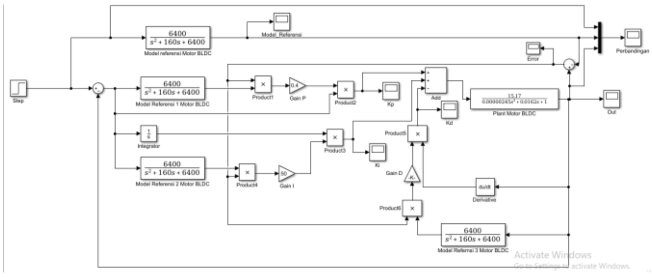

Figure 5. Simulation circuit of MRAC control system

A. MRAC system simulation testing

Testing the response of the MRAC control system is carried out under normal circumstances. The input given is a unit step signal. The values given in the initial input are in the form of a step time value of 0.01 seconds, a sample time of 0.01 seconds, and a final value of 1.

This simulation is done to see how the system response has been designed. The desired response specifications or characteristics of the system refer to the results of tuning previously performed using a PID tuner. The search for Kp, Ki, and Kd parameter values refers to the Kp, Ki, and Kd parameter values obtained previously in determining the system response characteristics.

Table 2. System Test Results

No	Kp	Ki	Kd	*Rise Time*	*Over-shoot*	*e*
1.	0,1	4	0,00001	0,074	-0,026	-0,04
2.	0,2	6	0,00002	0,074	-0,021	-0,034
3.	0,3	8	0,00003	0,074	-0,0168	-0,028
4.	0,4	10	0,00004	0,084	-0,015	-0,025
5.	0,4	20	0,00005	0,086	-0,0113	-0,017
6.	0,4	30	0,00006	0,086	-0,01	-0,014
7.	0,4	40	0,00007	0,089	-0,0068	-0,014
8.	0,4	50	0,00008	0,089	-0,006	-0,012
9.	0,4	50,75	0,0000867	0,097	0	-0,01
10.	0,41	50	0,0000867	0,097	-0,0078	-0,011
11.	0,41	50,1	0,0000867	0,097	0,033	-0,016
12.	0,412	50,2	0,0000867	0,097	-0,0082	-0,011
13.	0,413	50,3	0,0000867	0,097	-0,0071	-0,01
14.	0,414	50,4	0,0000867	0,097	-0,0049	-0,011
15.	0,415	50,5	0,0000867	0,097	-0,0065	-0,011
16.	0,416	50,6	0,0000867	0,097	-0,0062	-0,012

The determined parameter values have an influence on the response of the BLDC motor system using the MRAC controller, where the BLDC motor plant can follow the reference model that has been made. It was found that the error value began to stabilize when the Kp parameter value ranged from $0,4 - 0,421$; he Ki value ranged from $50 - 51,1$; the Kd value ranged from $0,00008 - 0,0000867$.

The range of values that have the lowest state of error that occurs is when the value of the adaptation gain P, I, and D is $Kp = 0,4\,; Ki = 50,75\,; Kd = 0,0000867$.

In this condition, the rise time on the reference model is the same as the rise time on the BLDC motor plant, which is about 0.097 seconds. In addition, there is also a very small overshoot almost close to 0 on the BLDC motor plant and the error value generated by the MRAC system response is -0.01, so that the system can reach a stable state more quickly. The system response results are shown in Fig. 6.

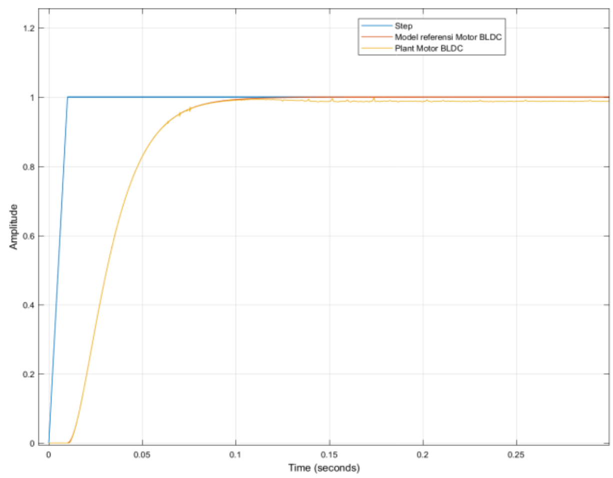

Figure 6. MRAC control system response

The system response shows the stability of the BLDC motor, where the plant of the BLDC motor can follow the reference model created.

Based on the tests that have been carried out, it can be seen that there are differences in the values obtained between automatic tuning and MRAC control.

Table 3. Results comparison

Parameters	**PID *tuner***	**MRAC**
Kp	0,4199	0,4
Ki	50,7294	50,75
Kd	0,0000867	0,0000867
Rise time	0,0439	0,097
Overshoot	0,0597	0
error	-0,06	-0,01

The difference in results between the PID tuner and MRAC simulation can occur because the tuning in the PID tuner only performs tuning automatically and cannot adapt to changes that occur in the system.

B. System Testing with Loading

The next system test is to provide loading with the aim of seeing the reliability of the MRAC simulation with a gain value of Kp=0,4 Ki=50,75 Kd=0,0000867. The loading given is in the form of a portable fan or waterproof DC fan. the characteristics of the fan that will be used as a load are as follows.

Table 4. Characteristics of Waterproof DC fan

Input	**Value**	**Units**
Voltage	12	V
Current	$0{,}09 \pm 10\%$	A
Input power	$1{,}08 \pm 10\%$	W
Speed	$2400 \pm 10\%$	Rpm
Operating voltage range	$7{,}5 - 13{,}8$	V

The system simulation circuit with loading used is as follows.

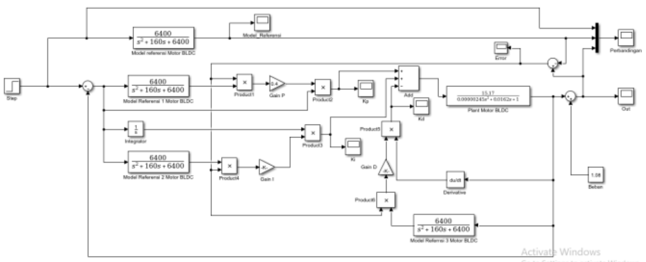

Figure 7. System simulation circuit with load

System testing is done by varying the value of the load given. The varied value is the value of the power usage required by the fan to function properly, while still paying attention to the characteristics of the BLDC motor used in this study.

Table 5. Results with load

No.	**Load (Watts)**	***Settling Time***	***Rise Time***	***Overshoot***	***error***
1.	0,972	0,11	0,094	-0,005	-0,97
2.	0,982	0,116	0,094	-0,005	-0,98
3.	0,994	0,116	0,094	-0,003	-0,99
4.	1,004	0,118	0,094	0	-1
5.	1,015	0,118	0,094	-0,004	-1,01
6.	1,026	0,119	0,094	-0,005	-1,03
7.	1,037	0,121	0,094	-0,002	-1,04
8.	1,047	0,122	0,094	-0,003	-1,05
9.	1,058	0,122	0,094	0	-1,06
10.	1,069	0,122	0,094	-0,002	-1,07
11.	1,08	0,122	0,094	0	-1,08
12.	1,091	0,123	0,094	0	-1,09
13.	1,102	0,123	0,094	0	-1,1
14.	1,112	0,123	0,094	-0,001	-1,11
15.	1,123	0,123	0,094	0	-1,12
16.	1,134	0,124	0,094	-0,002	-1,13
17.	1,145	0,124	0,094	-0,002	-1,14
18.	1,156	0,124	0,094	-0,002	-1,16
19.	1,166	0,124	0,094	-0,003	-1,16
20.	1,177	0,125	0,094	-0,003	-1,17
21.	1,188	0,126	0,094	-0,004	-1,18

Table 5. when the given loading of 1.08 watts shows the use of power on the load in accordance with the specifications of the load, where the input power of the load is $1{,}08 \pm 10\%$ watts which then produces a system response as in Fig. 8.

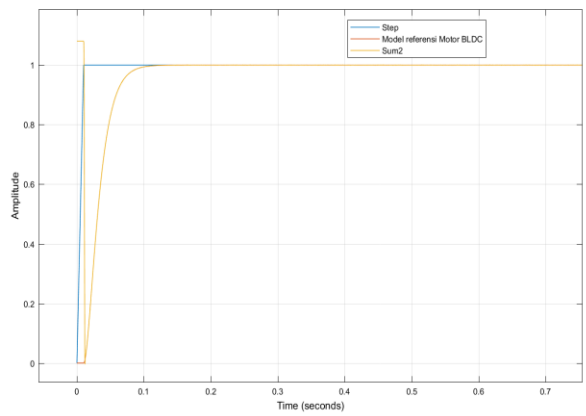

Figure 8. System response with 1.08 watts load

When the system is given a load of 1.08 watts, the MRAC controller will adapt to recognize the load which will then stabilize the response of the system. Obtained system rise time or rise time occurs at the 0.94th second, the settling time required by the system is 0.122 seconds. When the load condition is 1.08 watts, the system response does not experience overshoot and the error value that occurs in the system is -1.08. This situation shows that the higher the load given to the system, the higher the error will be proportional to the load.

IV. Conclusions

Based on data analysis and discussion of reliability testing of the MRAC control system that has been designed. The adaptive PID control system for BLDC motors using MRAC designed under normal conditions can produce a system success rate of 98,9%. When a load of 1,08 watts is applied to the system with a gain value of $Kp = 0{,}4\,; Ki = 50{,}75\,; Kd = 0{,}0000867$, a system success rate of 81,2% is achieved..

Acknowledgment

Thank you to Mrs. Umi Murdika and Mr. Syaiful Alam, supervisors of Electrical Engineering Unila who have guided the author in doing this final project until it is completed. Thanks are also expressed to family and friends who participated in contributing to the work of this final project.

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