PRZEGLĄD ELEKTROTECHNICZNY

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Comparison of BLDC Motor Controller Design for Electric Vehicles Using Fuzzy Logic Controller and Artificial Neural Network

Abstract . The existence of technologies such as electric motors such as the Brushless DC Motor become one of the solutions to replace the fossil-fueled engine. In order for the BLDC motor to rotate at controlled speed, a closed system is needed which can correct the actual speed or error when the BLDC motor is spinning. In this final project the speed control method used is Pulse Width Modulation (PWM) and the actual speed feedback will be controlled using fuzzy logic controller so that the actual speed can be set according to the desired speed. In this paper, compared two control method FLC and artificial neural network (ANN). Therefore the simulation and implementation are made and the data obtained that the results of the implementation that have been made are approaching from the simulation results. The difference between the results of the implementation and the simulation is because when implementing the speed sensor used has an average error of 2.11% so that the resulting actual speed also varies. From the results of the implementation data, errors that occur up to 1.28%. Simulation result have an average error of 58.9% with ANN.

Streszczenie. Istnienie technologii, takich jak bezszczotkowy silnik prądu stałego, stało się jednym z powodów zastępujących silnik zasilany paliwem kopalnym. Aby silnik BLDC obracał się z kontrolowaną prędkością, potrzebny jest zamknięty system, który może skorygować rzeczywistą prędkość lub błąd, gdy silnik BLDC się obraca. W tym projekcie zastosowaną metodą sterowania prędkością jest modulacja szerokości impulsu (PWM), a rzeczywiste sprzężenie zwrotne prędkości będzie sterowane za pomocą sterownika logiki rozmytej, tak aby można było ustawić rzeczywistą prędkość zgodnie z żądaną prędkością. W artykule porównano dwie metody sterowania FLC i sztuczną sieć neuronową (ANN). Dlatego przeprowadzana jest symulacja i implementacja, a uzyskane dane wskazują, że wyniki wdrożeń, które zostały wykonane, zbliżają się do wyników symulacji. Różnica między wynikami implementacji a symulacją polega na tym, że podczas implementacji zastosowany czujnik prędkości ma średni błąd wynoszący 2,1%, więc wynikająca z tego rzeczywista prędkość również się zmienia. Z wyników danych wdrożeniowych błędy, które występują, sięgają 1,28%. Wynik symulacji ma średni błąd 58,9% z SSN. (*Porównanie projektu sterownika silnika BLDC dla pojazdów elektrycznych wykorzystujących sterownik Fuzzy Logic i sztuczną sieć neuronową*)

Keywords:- Fuzzy Logic Controller, Artificial Neural Network, BLDC, PWM, Microcontroller.
Słowa kluczowe: silnik bezszczotkowy BLDC, logika rozmyta, sztuczne sieci neuronowe

Introduction

The increasing number of vehicles that use fossil fuels in recent times has resulted in an increase in the amount of air pollution. To reduce the amount of air pollution that exists, the use of conventional vehicles that produce air pollution must be reduced, one way to replace it with electric vehicles.

On the other side, there is a Brushless DC motor technology which is one type of electric motor without using a brush where the electrically based commutation of the rotary position. This Brushless DC motor is very much applied in the industrial field because of its high level of efficiency and reliability, the Brushless DC motor also has simple construction, easy maintenance, and has a high ratio of inertia. One method used to regulate the speed of a Brushless DC motor is by regulating the voltage on the side of the stator using the PWM method. The advantage of this method is that it has an uncomplicated structure and is commonly applied to Brushless DC motors. The speed variation of the Brushless DC motor can be changed by adjusting the duty cycle of the PWM.

To control the duty cycle of this PWM, a closed or closed loop control system is needed using the Fuzzy Logic Controller method. The method is used as a feedback response to the actual speed of the motor which is then compared with the set point value that has been determined and the output of the results of this comparison can be used to adjust the magnitude of the PWM to get the speed on the Brushless DC motor.

This research is part of the research on the development of an electric bus platform to support autonomous vehicles.

Literature review
A. Brushless DC Motor

BLDC motors have different construction from dc motors in general, where this motor has three different phases so that each phase has an angle of 1200, so the BLDC motor uses the hall effect which is used to detect the position where the rotor is located by using signals from the commutation motor In the brushless DC rotor there are shafts and permanent magnets. The brushless DC motor has a working principle based on the tensile force and the opposing force between the magnetic poles. Current passes through one of the stator coils, and produces a magnetic pole that will pull the opposite pole from the closest permanent magnet. by alternately flowing current in the stator coil, it will cause the rotor to rotate. At brushless DC the voltage of each phase in the motor coil can be formulated in the equation:

(1.1)
$$u_x = R_x i_x + e_{\psi x}$$

where i, u, and R are the parameters of current, voltage, and resistance in phase x (phases A, B, and C). Whereas is the emf induced in phase x. The magnitude of the emf induced in each phase is proportional to the rate of flux change.

(1.2)
$$e_{\psi x} = \frac{d\psi_x}{dt}$$

The amount of flux in phase A is

(1.3)
$$:\psi_A = L_A i_A + M_{AB} i_B + M_{AC} i_C + \psi_{PM}(\theta)$$

where is the flux linkage caused by permanent magnets in phase A. Teta is the angle that states the position of the rotor, is self-inducting, and is the inductance with phases A with phases B and C. The magnitude of this depends on the magnetic field distribution of the permanent magnet in the gap air. The radial component of the magnetic field in the air gap caused by permanent magnets is distributed trapezoidal along the inner surface of the stator. On a 3 phase DC Brushless motor having an equivalent circuit on the side of the stator is as follows:
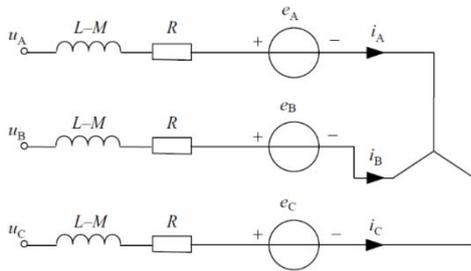

Fig. 1. Equivalent Circuit of BLDC Motor

In the equivalent circuit the current law applies,

(1.4)
$$i_A + i_B + i_C = 0$$

Then the equation can be simplified to be,

(1.5)
$$u_A = R i_A + (L - M)\frac{di_A}{dt} + e_A$$

So the phase voltage matrix equation for each BLDC motor stator coil is as follows:
(1.6)
$$\begin{bmatrix} u_A \\ u_A \\ u_A \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_A \\ i_A \end{bmatrix}$$
$$+ \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dx} \begin{bmatrix} i_A \\ i_A \\ i_A \end{bmatrix}$$
$$+ \begin{bmatrix} e_A \\ e_A \\ e_A \end{bmatrix}$$

The matrix equation for inter-phase voltage is obtained from the reduction of inter-phase voltage and is obtained:

(1.7)
$$\begin{bmatrix} u_{AB} \\ u_{AC} \\ u_{CA} \end{bmatrix}$$
$$= \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_A \\ i_A \end{bmatrix}$$
$$+ \begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \frac{d}{dx} \begin{bmatrix} i_A \\ i_A \\ i_A \end{bmatrix} + \begin{bmatrix} e_A - e_B \\ e_B - e_C \\ e_C - e_A \end{bmatrix}$$

B. Electronic Speed Control (ESC)

The brushless ESC system basically creates three-phase AC power at its output by adjusting the frequency, to run the brushless motor. At ESC motor rotation is detected by EMF or by using a hall sensor. Speed control on ESC can be programmed through a computer using a microcontroller to determine the low voltage limit, time setting, acceleration, braking, and the direction of rotation. Reversing the direction of the motor can also be done by replacing two of the three outputs from ESC to the motor.

The ESC circuit consists of switches that have been ignited to produce an AC signal on the output side. For example the tuning system can be seen in Figure 2. When phase A on a Brushless DC motor is connected to a positive voltage source and on the other side phase B is connected to ground, then for phase C in a floating condition, the current will flow from the positive voltage source through the phase A goes to a neutral point then goes through phase B and finally goes to ground. So by using only one current flow, four different poles can be generated to drive the rotor. With this configuration, the star configuration in the Brushless DC motor phases will be formed as shown in Figure 2, where the neutral point internally connects each phase end and the other end exits the motor. This is why the DC brushless motor has three cables. So to produce a full cycle so that it can rotate, two correct MOSFETs must be activated at every six intervals. Therefore we need an electronic speed controller (ESC).
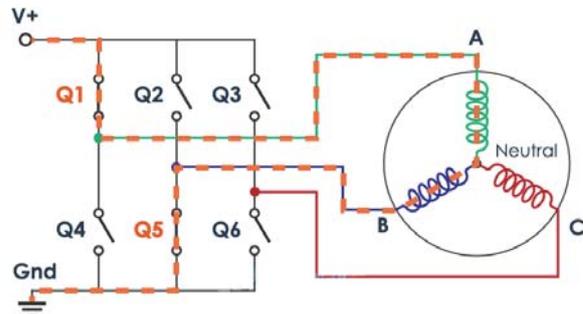

Fig. 2. Example of current flow in the brushless motor

ESC functions is to control the speed of a brushless motor by activating the MOSFET needed to produce rotating magnetic fields (RMF) so that the motor can rotate. The higher the input frequency on the MOSFET, in other words the faster the ESC goes through six intervals, the higher the speed of the Brushless DC motor to be produced. To find out which phase the current will pass through first, it can be used by knowing the position of the rotor, there are two general methods used to determine the position of the rotor.
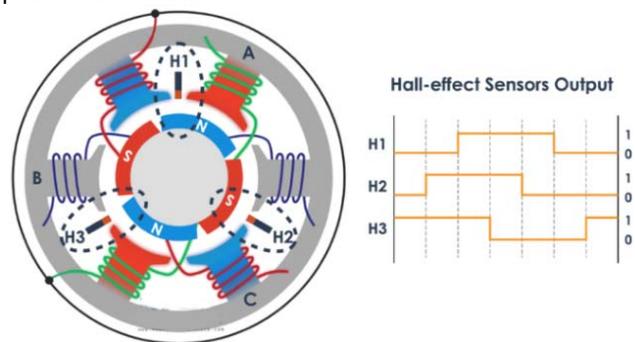

Fig. 3. Hall-effect Sensor Output

The first method is to use a hall-effect sensor located on the stator by placing every 120 degrees or 60 degrees

between one sensor and another. When a rotor consisting of a permanent magnet rotates, the hall-effect sensor will induce a magnetic field and produce logic high for one pole and low for the other pole. Based on this information ESC will know when to activate the next commutation interval.
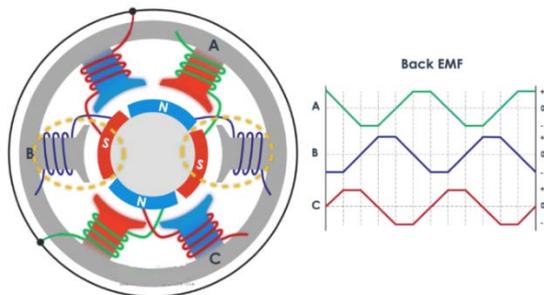

Fig. 4. Output of Back EMF

The second method for determining the position of the rotor is to use the reverse electromotive force generated, or referred to as the back EMF. Back EMF is generated by the truth of the process of producing a magnetic field, which is when moving or changing the magnetic field that passes through the coil will induce the current in the coil. So when the magnetic field in the rotor moves past the coil that is not active, this magnetic field will induce current on the coil so that a voltage difference will arise. ESC will capture this voltage difference when it occurs and based on that ESC will calculate when the next interval should occur.

C. Fuzzy Logic

Motor speed control can use several methods, one of which is by using fuzzy-logic controller. Fuzzy logic has been widely used in automation and control systems. Fuzzy logic can be used to solve nonlinear problems and uncertainties without using a mathematical model.

Fuzzy logic is a set of logic theories developed to overcome the concept of values that exist between the value of truth (true) and error (false). Fuzzy logic is different from ordinary digital logic or Boolean. Ordinary digital logic recognizes only two explicit states (crips), namely 'yes' or 'no', '0' or '1', and 'on' or 'off'. Unlike ordinary digital logic, fuzzy logic mimics the way of human thinking by using the concept of the similarity of a value. By using fuzzy logic, values are no longer only '0' and '1' but all possibilities are between 0 and 1.

The simplicity of the concept makes fuzzy logic easy to understand. Fuzzy is not fixated on a single decision, flexible, so that it can provide a tolerance value on uncertainty. There are several reasons why choosing to use fuzzy logic, namely:
1. The concept of fuzzy logic is easy to understand. The mathematical concept of logic is very simple.
2. The nature of flexible fuzzy logic
3. Fuzzy logic is able to describe linear functions that are complex.

I. SIMULATION AND PROTOTYPE DESIGN

A. Simulation

In this study, the simulation will be carried out using Simulink, the following is a block diagram of the simulation carried out:

In the picture above, the system gets a speed reference value in the form of a certain constant that is inputted to the Constant block. Then the reference value will be compared with the RPM value generated by the Permanent Magnet Synchronous Machine, the use of the Permanent Magnet Synchronous Machine as a representation of the BLDC Motor in simulations using Simulink.

Comparison between the reference value and the RPM value will produce an error value, then the error value is divided by the reference value in order to get an error value 'in the range 0 to 1. Error value' is used for the first input, the membership function for Input Variable Error or (e) in this study and has a domain of -1 to 1 (can be seen in Figure 3.2. Membership Function for Input Variable Error)
The error value 'will also be used for the second input from the fuzzy logic controller, namely delta error input (de). This delta error value is obtained in a way, i.e. the current error value will be reduced by the previous error.

Then the two inputs (e) and (de) will be processed in the fuzzy logic controller block which was previously given a program. FIS contains Fuzzy Rule (table XX Rule Fuzzy) so that it produces fuzzy output which will then be obtained in the next block according to Figure 3.1 Simulation Using Simulink above.
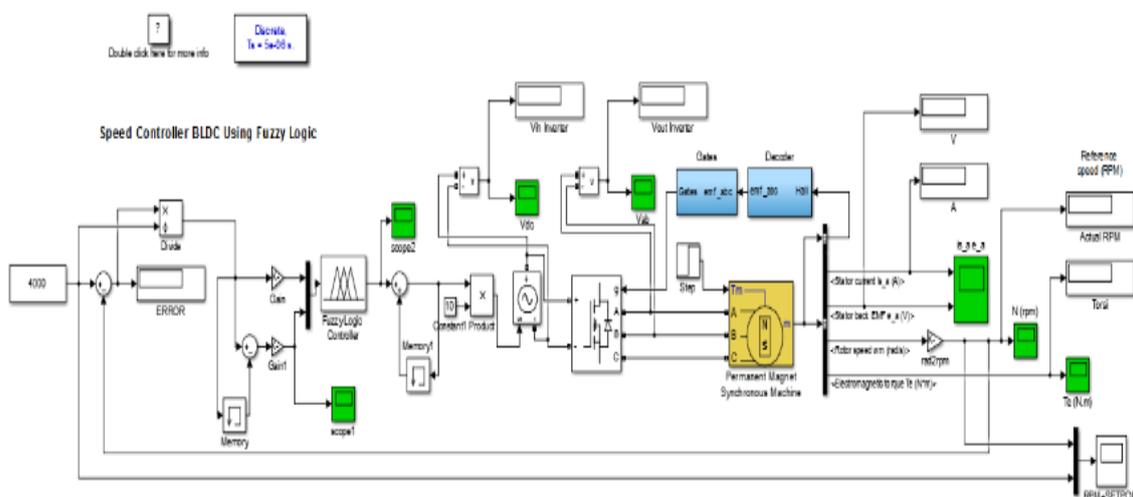

Fig. 5. Simulations Using Simulink

B. Membership Function Input

In this final project, the fuzzy logic control system uses two inputs, namely Error and Delta Error. Input Error is defined as the difference in value between the reference speed and the actual speed. Whereas Delta Error input is defined as the difference between the current error value and the previous error value. The membership functions of Error and Delta Error are represented using a rectangular curve like the image below:
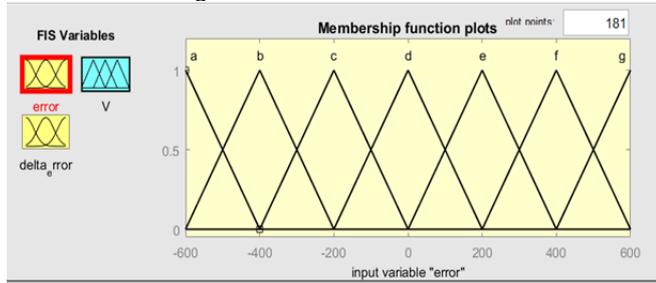

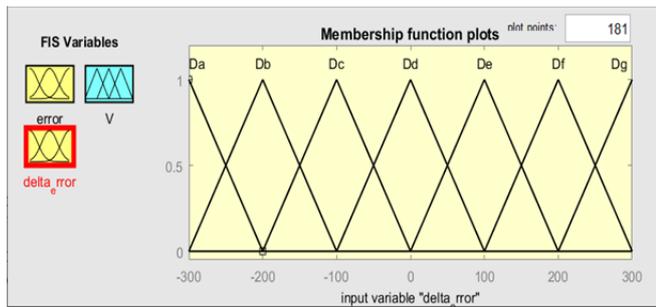Fig. 6. Membership Function for Input Variable Error

Fig. 7. Membership Function for Input Variable Delta Error

C. Rule of fuzzy

The next step is to determine the fuzzy rule by adjusting the number of membership functions of the fuzzyfication process. Fuzzy logic in this study is expected so that the actual speed of the BLDC motor can follow the reference speed sent from the potentiometer. So a fuzzy rule was made with seven membership functions of errors and seven membership functions of delta errors. Each function is Negative Big (a/Da), Negative Medium (b/Db), Negative Small (c/Dc), Zero (d/Dd), Positive Small (e/De), Positive Medium (f/Df), and Positive Big (g/Dg) as shown in the table below :

Table 1. Rule of Fuzzy

e \ de	a	B	C	D	e	f	g
Da	Ha	Ha	Ha	Ha	Hb	Hc	Hd
Db	Ha	Ha	Ha	Hb	Hc	Hd	He
Dc	Ha	Ha	Hb	Hc	Hd	He	Hg
Dd	Ha	Hb	Hc	Hd	He	Hf	Hg
De	Hb	Hc	Hd	He	Hf	Hg	Hg
Df	Hc	Hd	He	Hf	Hg	Hg	Hg
Dg	Hd	He	Hf	Hg	Hg	Hg	Hg

D. Membership Function Output

In this final project, the fuzzy logic control system uses one output. The membership function output is represented by 7 triangular curves, namely Negative Big (Ha), Negative Medium (Hb), Negative Small (Hc), Zero (Hd), Positive Small (He), Positive Medium (Hf), and Positive Big (Hg) as the table below:
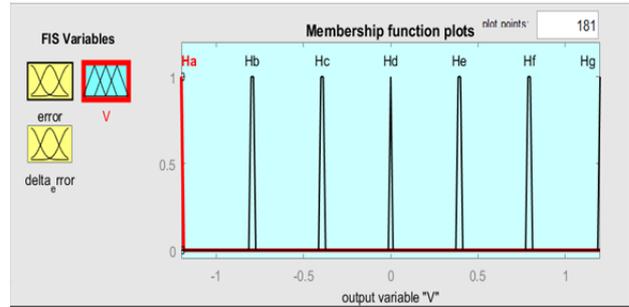

Fig. 8. Membership Function Output

E. Specifications Of The Tools And Wiring Diagram
a. Brushless DC Motor

In this study, the brushless DC motor used was A2212 / 10T with the following specifications:

Fig. 9. Brushless DC Motor A2212/10T

Table 2. Product Specification of Brushless DC Motor A2212 / 10T

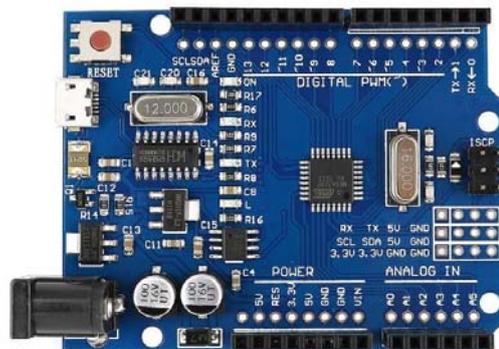|	
Operating Voltage	7,2 – 12Volt (2-3 LiPo Battery)
RPM/V	1400 kV
Max Operating Temperature	±80°C
Max Efficiency current	4 – 10 A
No Load Current	0.5A
Max Current	13A for 60 seconds
Max Watts	150W
Weight of Motor	50 – 60 gram
Size	28 mm dia x 28 mm bell length
Shaft Diameter	3.2 mm
Poles	14

Fig. 10. Arduino Uno

b. Microcontroller

The use of microcontroller in this study uses Arduino Uno because the size of the Arduino idea program file that we made is no more than the size of Arduino Uno flash memory, besides that the digtal I / O port or pin needed is also sufficient to make the tools in this study. The following are the arduino uno specifications used:

Tabel 3. Specification of Arduino Uno

Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz
Length	68.6 mm
Width	53.4 mm
Weight	25

c. Electronic Speed Controller (ESC)

So that the speed on the BLDC motor can be regulated easily, we need an instrument called an electronic speed controller (ESC) so that the BLDC motor speed regulation can be programmed using a microcontroller. The supply voltage uses a battery which will then be converted into AC waves by electric speed control before entering the motor. In this study, the ESC used was Emax BLHeli 12A with the following specifications:

Table 4. Spesification of Emax BLHeli 12A

Continuous Current	12A
Burst current (10S)	15A
Li-xx Battery (cell)	2-3
Dimension (L*W*H)	25mm x 20mm x 7mm
BEC Mode	Linear
BEC Output	1A/5V
Programmable	Yes

Fig. 11. Emax BLHeli 12A

d. Wiring Diagram
Winding diagram is presented in Fig.12

F. Speed Reference Using Potensiometer

This reference speed is regulated using an analog signal sent by a potentiometer which is then converted in a digital value by Arduino before being sent to the ESC. The value of the potentiometer is 0-1023 in analog form will be changed to 0-180 in the form of digital output.

ESC will not respond to PWM if the input is directly within a certain value. Therefore, the need for PWM output values from Arduino entering the ESC is initiated starting at 0. And this PWM value will increase if the value of the potentiometer also increases.
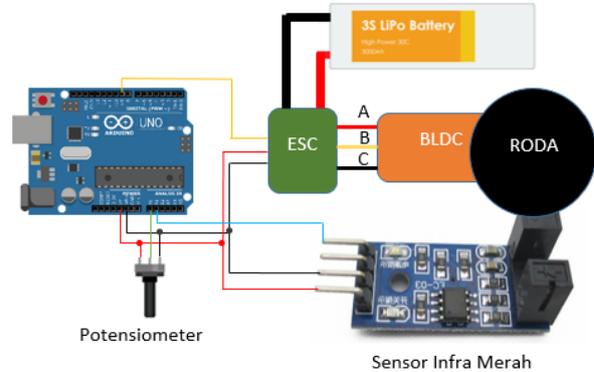

Fig. 12. Wiring Diagram of The Prototype

G. Calculation of Speed Using IR Sensor

When the BLDC motor is spinning, Arduino cannot read the speed or the resulting RPM, so it is necessary to assist a tool in the form of a speed sensor. The speed sensor used in this study is an IR sensor type.

This tool will send an LOW signal (0V) to Arduino when the IR sensor is blocked by an object and will send a HIGH signal (5V) to Arduino when the IR sensor is not blocked by the object, then it will be processed and programmed by Arduino into data in the form of speed or RPM then it will be used for making speed control systems using fuzzy logic

H. Speed Control Program BLDC Using Fuzzy-logic

After getting the rpm value on the motor, this speed value will be compared with the reference signal sent by Arduino into the ESC. This fuzzy logic occurs in Arduino which is then processed into a PWM output signal. Of course the value compared to Arduino is not the PWM value as explained in the ESC drive system in the previous section. However, the PWM value generated from the analog signal sent by the potentiometer is converted into the rpm reference form by scaling the rpm results sent into the ESC and also the speed generated. Because each increase in the PWM value causes the value of the cycle to increase with a vulnerable value close to the same. Then the value is then scaled and made as an input reference value into the ESC.

The PWM value entered into the ESC will always change and not the same as in the previous ESC control. This is caused by an error reading the hall sensor used.

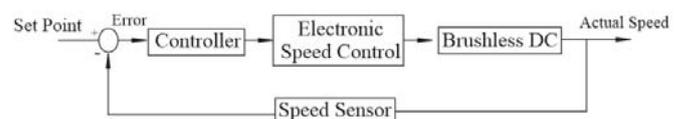The following is a block diagram of a speed control system on a BLDC motor:

Fig. 13. Block Diagram Of Speed Control System

In the speed control system in this fuzzy logic control, the reference value is derived from the value of the potentiometer which was originally analog from 0 - 1023 to a digital signal from 0 - 180. The potentiometer value is then calculated by scaling the PWM input to the ESC and the actual speed generated by motorbike. The reference speed is then changed in the form of PWM before entering into ESC, this is because to be able to rotate the motor, the value entered into the ESC must start from a small value.

In this PWM will cause the motor to rotate, which then reads the speed sensor. This actual speed will be compared with the reference speed in the fuzzy control. In FLC there are several processes. First is fuzzyfication or error and delta error recognition. This error is a comparison between actual and reference speed. In the fuzzy control has been established rule-base or a condition that will result from the fuzzyfication process.

Results Of Implementation And Discussion
A. Speed Control Test
This test is an implementation of speed control using fuzzy logic. The results of this implementation will be compared with the results of simulations that have been done to find out the differences between the two and to find out how many errors occur in the implementation results. Here are the test results obtained
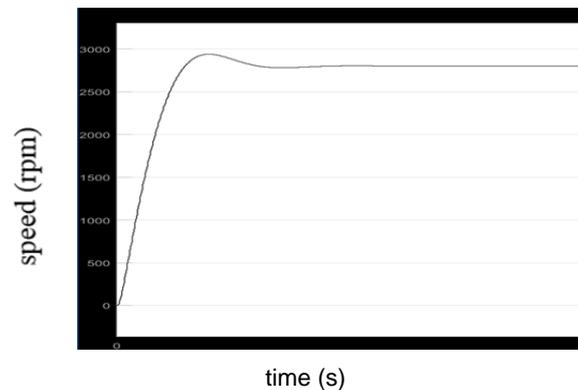

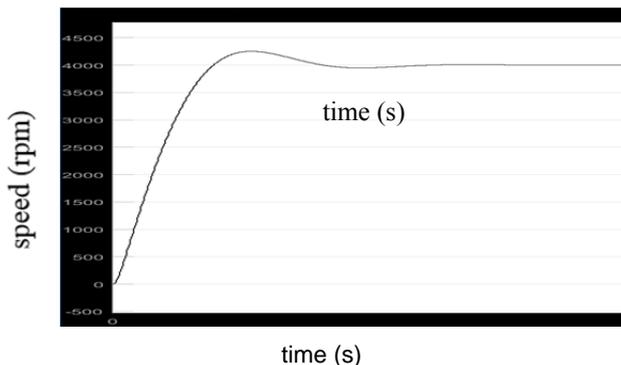Fig. 14. 2800 RPM speed control of simulation results

Fig. 15. 4000 RPM speed control of simulation results
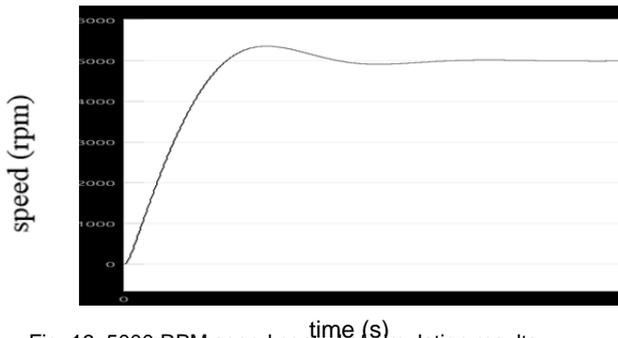

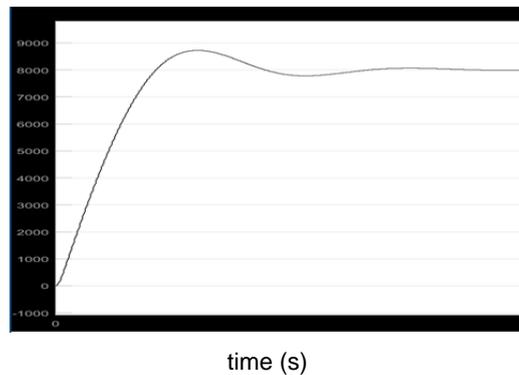Fig. 16. 5000 RPM speed control of simulation results

Fig. 17. 8500 RPM speed control of simulation results

a. Simulation Result
In this simulation, the reference speed is set at 2800 RPM, 4000 RPM, 5000 RPM, and 8500 RPM using a potentiometer and is represented by a red line. The results can be seen that the actual speed represented by a blue line can follow the desired speed or the red reference speed as shown in the picture below:

b. Implementation Result of Close - Loop System
This implementation, is using closed loop system or using a fuzzy logic controller, the reference speed is set at 2800 RPM, 4000 RPM, 5000 RPM, and 8500 RPM using a potentiometer and represented by a blue line. The results can be seen that the actual speed represented by a blue line can follow the desired speed or the red reference speed as shown in the picture below:

c. Error in Implementing Close Loop System Speed Control
Error value can be calculated easily when the speed is in a steady state. The following are the error values of speed controls for implementing the 2800 RPM, 4000 RPM, 5000 RPM and 8500 RPM :

Table 5. Error in Implementing of Speed Control System at 2800 RPM

Reference RPM	Actual RPM	Error (%)
2800	2800	0.05
2800	2800	0.03
2800	2800	0.03
2800	2800	0.17
2800	2800	0.00
2800	2800	0.00
2800	2800	0.00
2800	2800	0.00
2800	2800	0.00
2800	2800	0.00
2800	2800	0.05
2800	2800	0.03
2800	2800	0.10
2800	2800	0.00
2800	2800	0.04
2800	2800	0.04
2800	2800	0.03
2800	2800	0.03
2800	2800	0.03
Average Error (%)		0.03

Tabel 6 Error in Implementing of Speed Control System at 4000 RPM

Reference RPM	Actual RPM	Error (%)
4000	4000	0.02
4000	4000	0.16
4000	4000	0.02
4000	4000	0.06
4000	4000	0.11
4000	4000	0.01
4000	4000	0.06
4000	4000	0.09
4000	4000	0.02
4000	4000	0.00
4000	4000	0.03
4000	4000	0.03
4000	4000	0.04
4000	4000	0.06
4000	4000	0.02
4000	4000	0.00
4000	4000	0.00
4000	4000	0.03
4000	4000	0.04
Average Error (%)		0.04

Table 7. Error in Implementing of Speed Control System at 5000 RPM

Reference RPM	Actual RPM	Error (%)
5000	5000	0.02
5000	5000	0.03
5000	5000	0.00
5000	5000	0.01
5000	5000	0.00
5000	5000	0.00
5000	5000	0.04
5000	5000	0.03
5000	5000	0.02
5000	5000	0.02
5000	5000	0.00
5000	5000	0.01
5000	5000	0.02
5000	5000	0.01
5000	5000	0.02
5000	5000	0.04
5000	5000	0.02
5000	5000	0.00
5000	5000	0.01
Average Error (%)		0.01

Table 8. Error in Implementing of Speed Control System at 8500 RPM

Reference RPM	Actual RPM	Error (%)
8500	8498	1.90
8500	8498	1.87
8500	8498	1.80
8500	8499	1.45
8500	8499	0.90
8500	8499	0.56
8500	8500	0.14
8500	8500	0.20
8500	8500	0.10
8500	8500	0.09
8500	8500	0.07
8500	8500	0.08
8500	8500	0.04
8500	8500	0.03
8500	8500	0.03
8500	8500	0.02
8500	8500	0.01
8500	8500	0.00
8500	8500	0.00
Average Error (%)		0.48

d. ANN Test

An artificial neural network (ANN) is the piece of a computing system designed to simulate the way the human brain analyzes and processes information. It is the foundation of artificial intelligence (AI) and solves problems that would prove impossible or difficult by human or statistical standards.

From these simulations we provide data in accordance with the specifications of the same system with fuzzy logic. So that the data is obtained as follows :

Table 9. Output in implementing 8500 RPM speed control with ANN (Artificial neural network)

Error	Delta Error	Output
559,99999079008100	-0,000100079	1,118364
559,99999075359200	-0,000100813	1,118363
559,99999071710300	-0,000101547	1,118363
559,99999068061400	-0,000102282	1,118362
559,99999064412600	-0,000103016	1,118362
559,99999060763700	-0,000103751	1,118362
559,99999057114800	-0,000104485	1,118361
559,99999053465900	-0,000105219	1,118361
559,99999049817000	-0,000105954	1,11836
559,99999046168100	-0,000106688	1,11836
559,99999042519200	-0,000107423	1,11836
559,99999038870300	-0,000108157	1,118359
559,99999035221400	-0,000108891	1,118359
559,99999031572500	-0,000109626	1,118358
559,99999027923600	-0,00011036	1,118358
559,99999024274700	-0,000111095	1,118357
559,99999020625800	-0,000111829	1,118357
559,99999016976900	-0,000112563	1,118357
559,99999013328100	-0,000113298	1,118356
559,99999009679200	-0,000114032	1,118356

From the data obtained, a simulation is carried out using the artificial neural network method. By doing the retrain so many times until we get validation with a value of 0.96071 which is close to 1 Therefore, the following series is made :
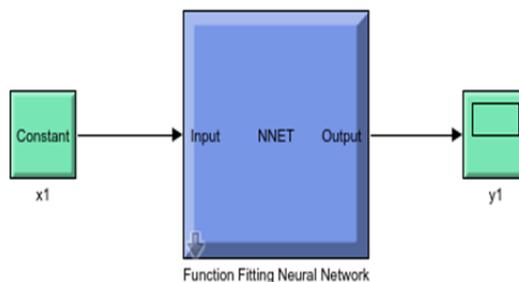

Figu. 18. Results function Fitting Neural Network of 8500 RPM speed control with ANN (Artificial neural network)
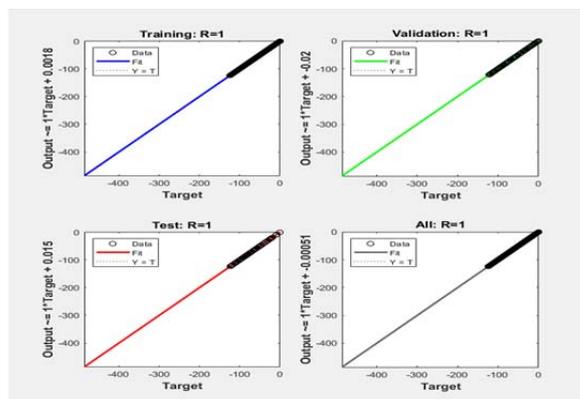

Fig. 19. Results regretion of 8500 RPM speed control with ANN (Artificial neural network)

By using the rpm data input, which is 8500, the simulation results are in the form of a curve and the value can achieve stability, but it does not match the input value of the input. So that in this simulation there is no steady state at the predetermined value.

Fig. 20. *8500 RPM* speed control of simulation results with ANN (Artificial Neural Network)

Table 10. Input Reference RPM, Actual RPM, and Error in 8500 RPM

Reference RPM	Actual RPM	Error (%)
8500	3485	59,0
8500	3487	59,0
8500	3481	59,0
8500	3509	58,7
8500	3506	58,8
8500	3497	58,9
8500	3485	59,0
8500	3502	58,8
8500	3494	58,9
8500	3480	59,1
8500	3506	59,0
8500	3492	58,9
8500	3485	58,8
8500	3482	59,0
8500	3490	58,9
8500	3515	58,6
8500	3482	59,0
8500	3505	58,8
8500	3484	59,0
Average Error (%)		58.9

B. Torque Test

In this study, only the speed change was made while the mechanical load used remained. So the torque can be calculated using the formula:

$$\tau = \frac{120}{2\,\pi\,(\frac{n}{60})}$$

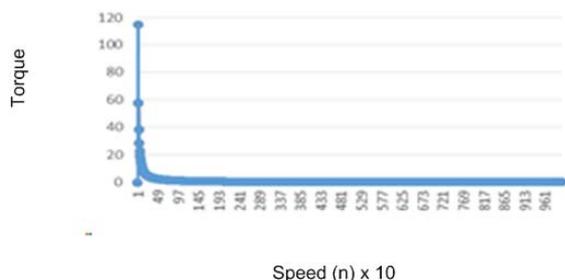From the formula we get the torque-speed characteristic curve data like this picture:

Fig. 21. Torque – Speed Curve

For more obvious, there is a table of torque data for speeds of 2800, 4000, 5000, and 8500 RPM.

Table 11. Torque table for speeds of 2800, 4000, 5000, and 8500 RPM

RPM	Torque
2800	0.41
4000	0.29
5000	0.23
8500	0.13
Average Torque	0.27

Based on the above table, it is known that the average torque generated at the speed has been tested in the amount of 0.27 Nm

D. Data Analysis and Discussion

After doing some testing and getting the data, the data analysis and discussion will be carried out as below:
a. Analysis of Speed Control Testing

In this study, testing is done by comparing the results of simulations, implementing tools using a close loop system (using fuzzy logic), and implementing tools that use an open loop system (not using fuzzy logic).

Based on the respective test graphic images, between the simulation results, the implementation of the tool using the close loop system and the implementation of the tool using the open loop system has an output that matches expectations, ie the output (actual speed) can follow the input (reference speed).

However, from the above test, it is obtained that the implementation of tools that use a closed loop system (with fuzzy logic) has a smaller average error when compared to the open loop system (without fuzzy logic). For clearer differences, the table below can be seen:

Table 12. Difference in Error Between Simulation, Implementation with FCL, and Implementation without FCL

RPM	Error (%)		
	Simulation	Implementation with FCL	Implementation without FCL
2800	0.52	0.01	2.05
4000	0.52	0.30	1.75
5000	0.52	0.49	1.00
8500	0.00001	1.28	1.48
Average Error (%)	0.39	0.52	1.57

The table above, it can be seen that the results of the simulation have a more stable error value because the system works in an ideal state or without interference from outside the system.

If you see the results of the implementation of the tool with FCL or close loop system has a greater error value when the RPM value is raised. This is because the device experiences vibrations when the RPM value gets higher so that the speed reading by the IR Sensor is also disturbed due to the vibration and the resulting output is also getting worse.

While the results of the implementation of tools without FCL or open loop system have a greater error value when compared to the simulation results and the implementation of tools with a close loop system. In addition, the resulting error value also changes - does not depend on the given RPM value. This result occurs because there is no improvement in the value of the error generated or feedback to the system and is a major weakness of the open loop system.

c. Torque Testing Analysis

Based on the testing of torque that has been done, the torque produced at 2800 RPM is 0.41 Nm while the torque generated at 8500 RPM is 0.13 Nm, so a torque reduction of 68.29% is obtained.

d. Using Vehicle Prototype for Uphill and Downhill Road Conditions

For road conditions uphill, the vehicle must require large torque to be able to move the vehicle up without obstacles, the way is by adjusting the gas or the right RPM in order to produce the largest torque from the vehicle.

In the prototype of the vehicle or the implementation of this tool, a trial or road test is carried out with the assumption of a fixed load and for use on uphill roads, it requires the greatest torque of 0.41 Nm so that the prototype of this vehicle must maintain a stable speed at 2800 RPM so that the vehicle can pass uphill road. This is the importance of speed control in a vehicle so that RPM can be easily regulated so that torque is also easily regulated.

Whereas on a declining road condition, the vehicle does not require large torque, just utilizing the gravity force of the vehicle can easily pass the downhill road. But if the speed is still given even though the road is going down it will cause potential danger to the vehicle because the speed is too fast and has caused the vehicle to be difficult to control. So that in a declining road condition, the prototype of the vehicle or the implementation of this tool is enough to set the speed at 0 RPM so the torque produced is also 0 Nm.

Conclusion

1. Simulation results have an average error of 0.49% while the results of the implementation of the tool have an average error of 0.82%.
2. Simulation result have an average error of 58.9% with ANN, the ANN must be learn with many and accurate data.
3. Speed regulation at high RPM will result in a decrease in torque of 68.29%.

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